ANNUAL RESEARCH REPORT
U.S. WATER CONSERVATION LABORATORY

1992

USDA - AGRICULTURAL RESEARCH SERVICE
Phoenix, Arizona

ANNUAL RESEARCH REPORT

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U.S. WATER CONSERVATION LABORATORY
U.S. Department of Agriculture
Agricultural Research Service
4331 E. Broadway Road
Phoenix, Arizona 85040

Telephone: (602) 379-4356
FAX: (602) 379-4355

INTRODUCTION

The U. S. Water Conservation Laboratory (USWCL) Annual Research Report is intended to inform upper level management within the Agricultural Research Service, other ARS research locations involved in natural resources research, and our many collaborators and cooperators about progress on our research projects in 1992 and plans for 1993 and beyond. It is our intent to keep the individual reports short but informative, focusing on what is being done and why, beginning with a statement of the problem; followed by research objectives; the approach to the problem; brief results--what it all means; future plans for the project; and cooperators involved. We want to make sure that the product of the research and its contribution to water conservation are clear to all.

In addition to allowing the research staff to tell our research story, the Annual Research Report and the Annual Staff Review and Planning Meeting which is held each year in early January, provide an opportunity for us to assess where we are in our programs; to look at the long-range (three-to-five-year) goals and expected outcomes (both long-term and intermediate), one-year goals, and strategies to get there. By planning our research in this way, goals, outcomes, and strategies are clarified, and appropriate resources can be identified.

In 1990, as we faced the funding squeeze caused by inflation on the one hand and generally fixed budgets on the other, we made a commitment to work collaboratively with other agencies and industry in bringing Post Doctorates, visiting scientists and engineers, graduate students, and persons on sabbaticals to the USWCL, to maintain or expand the research programs of the USWCL. To attract visiting and temporary personnel, we were depending on the expertise of our staff and our broad client base. I am pleased to say that we have been reasonably successful in this overall endeavor. Certainly, outside funding sources are instrumental in our continued work in major program areas, but the "in-kind" human resources provided by many of our cooperators and collaborators are highly significant, and our programs are enhanced, especially by each individual's stimulating effects on our research efforts.

A number of organizations are contributing significant financial resources in support of the research program at the USWCL. The *Irrigation Group* is receiving outside support through OICD over a three-year period for a collaborative study with the National Agricultural Research Project in Egypt dealing with the effects of land leveling precision and tillage practices on surface irrigation performance; from UMA Engineering to evaluate overshot gates as water measuring devices; from the Arizona Department of Water Resources and the USDI-Bureau of Reclamation to support the development of the Management Improvement Program; and is technically involved in a cooperative program with the Imperial Irrigation District, Metropolitan Water District, Imperial Valley Conservation Research Center Committee, and the ARS Brawley Field Station to establish a demonstration/test facility at the Brawley station for training and demonstrating state-of-the-art irrigation practices. The Department of Energy and temporary funding from ARS are supporting the *CO_2-Climate Change Group* program to evaluate the interactive effects of elevated CO_2 and increased temperature on plant growth and physiological processes including the development of predictive models. Agrigenetics, International Flora Technologies, and USDA/CSRS Office of Agricultural Material are providing support to the *New Crops Group* to commercialize Lesquerella and Vernonia as new industrial oil seed crops. A Cooperative Research and Development Agreement (CRADA) is currently being negotiated with a private company in collaboration with the *Remote Sensing Group* to focus on the application of remote sensing technology to on-farm water management needs. To these many cooperators, collaborators, and contributors, we say thanks and will continue working to make these associations mutually beneficial in serving agriculture.

As always, we invite you to use this Annual Research Report. Let us know if there are questions or comments; all are invited and will be appreciated.

Allen R. Dedrick
Director

U. S. WATER CONSERVATION LABORATORY
ORGANIZATIONAL DESCRIPTION AND MISSION STATEMENTS

The overall mission of the U. S. Water Conservation Laboratory (USWCL) is to conserve water and protect water quality in systems involving soil, aquifers, plants, and the atmosphere. Research thrusts focus on irrigation systems efficiency; irrigation systems management; irrigation scheduling methods; remote sensing of crop, soil, and atmospheric conditions; practices for protection of groundwater from agricultural chemicals; introduction of new crops; and the effect of future increases of atmospheric CO_2 on climate and associated yields and water requirements of agricultural crops.

The USWCL program is structured into two Research Units: Irrigation and Water Quality (I & WQ) and Environmental and Plant Dynamics (E & PD). I & WQ focuses on water management with emphasis on irrigation and water quality; E & PD concentrates on carbon dioxide-climate change, germplasm development for new crops, and remote sensing. Bert Clemmens and Bruce Kimball are the Research Leaders for the respective Research Units. The organizational structure for the USWCL is shown as Figure 1; staff additions during 1992 are shown as Table 1; and the entire USWCL personnel list as Table 2.

The mission of the Irrigation and Water Quality Research Unit is to develop management strategies for the efficient use of water and the protection of groundwater quality in irrigated agriculture. The unit uses holistic approaches to develop concepts and tools for improving the design, operation, and management of both farm irrigation systems and irrigation water delivery systems. In particular, this program includes developing best management practices for water and chemical applications, characterizing the movement and degradation of agricultural chemicals below irrigated fields, developing water measurement and control structures, and integrating farm and irrigation project operations and management. The research consists of field and laboratory studies and mathematical/computer modeling. To expedite technology transfer, efforts focus on management improvement processes in which users actively participate and on user-friendly computer software.

The mission of the Environmental and Plant Dynamics Research Unit is to develop optimum resource management strategies to meet national agricultural product requirements within the context of possible changes in the global environment. Specifically, the unit seeks to develop new methods to assess water and carbon dioxide fluxes in the soil-plant-atmosphere system, quantify plant stress and its effect on crop yield, and to predict effects of increasing carbon dioxide and climate change on plant growth and water use; develop suitable new and alternative crops to meet national needs for renewable, agriculturally-based industrial products; and develop remote sensing and related techniques as tools in water conservation, irrigation scheduling, drought prediction and avoidance, and to monitor crop conditions and assess environmental change. The program is designed to meet challenges and opportunities imposed by dynamic environments, particularly those stressful to plants, and their possible effects on crop production. A theme of increasing plant water use efficiency and conserving and improving the quality of agricultural water supplies unites these efforts. To these ends, the organization is closely knit and multidisciplinary, underlain by a philosophy of devising multifaceted approaches to critical problems associated with global environmental changes.

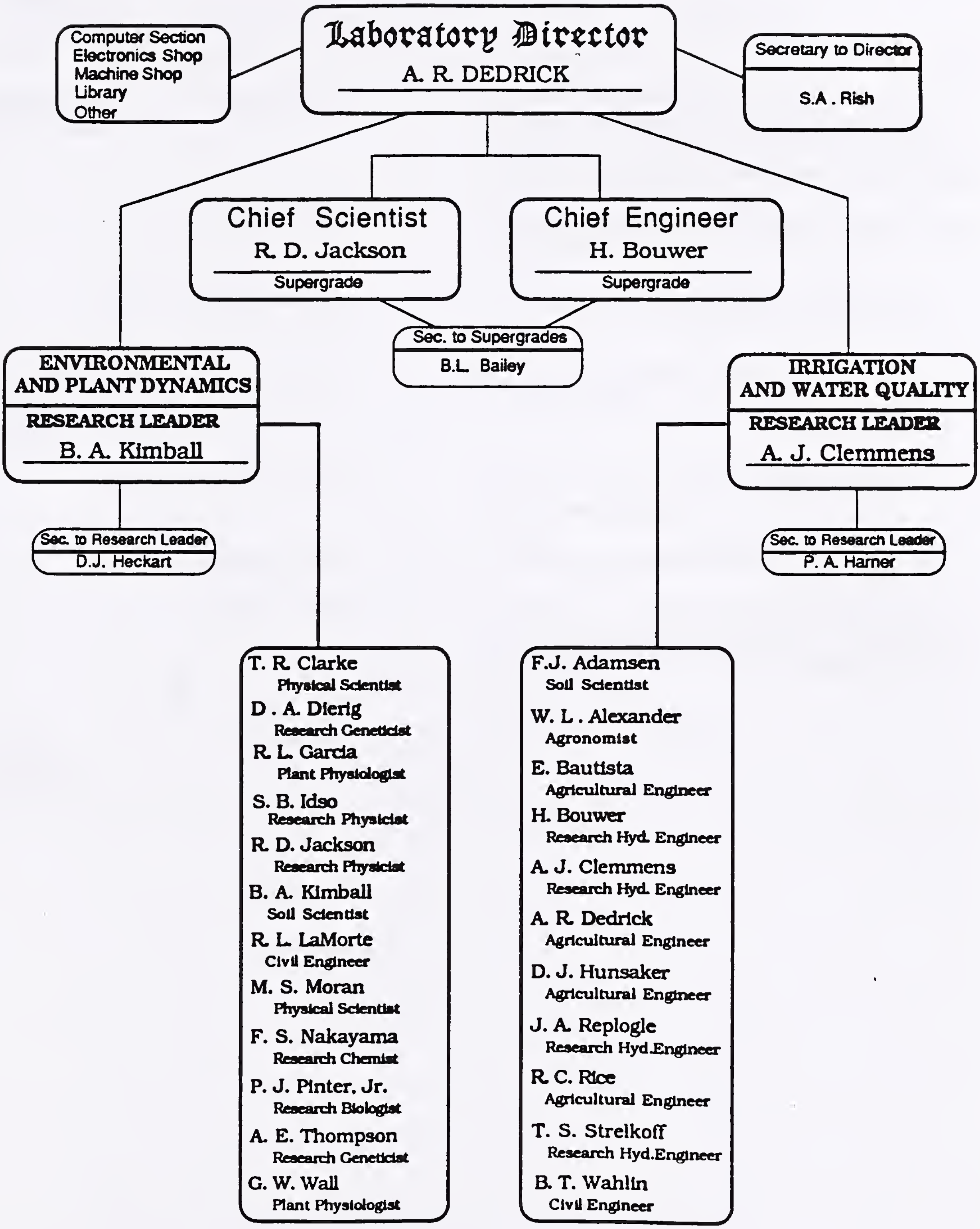

Fig. 1. U.S. Water Conservation Laboratory Organization, December 31, 1992

Table 1. Staff additions or changes at the U. S. Water Conservation Laboratory during 1992.

RESEARCH UNIT	STAFF MEMBER	ASSIGNMENT
Irrigation and Water Quality	Eduardo Bautista	Agricultural Engineer, Post-Doctorate position, will work with the Management Improvement Program, initially concentrating on documentation of the MIP process for reapplication of the model in other settings
	David Coleman	Physical Science Technician, will work with the Water Quality Group
	Brian Wahlin	Civil Engineer, will concentrate on flow metering studies
Environmental and Plant Dynamics	Gail Dahlquist	Agricultural Research Technician, will work with the New Crops Group
	Lynnette Eastman	Biological Science Technician, will work with the Remote Sensing Group
	Donna Heckart	Secretary to the Research Leader
	Robert LaMorte	Civil Engineer, will oversee the operation of the physical equipment for the Free-Air CO_2 Enrichment Project and CO_2-enriched chambers associated with other experiments
Overall Laboratory	Lou Salisbury	Office Automation Assistant

Table 2. U.S. Water Conservation Laboratory Staff, December 31, 1992

PERMANENT EMPLOYEES

Name	Title
Adamsen, Floyd J.	Soil Scientist
Alexander, William L.	Agronomist
Arterberry, Carl A.	Agricultural Research Technician
Auer, Gladys C.	Physical Science Technician
Bailey, Benita L.	Secretary
Bouwer, Herman	Research Hydraulic Engineer
Clarke, Thomas R.	Physical Scientist
Clemmens, Albert J.	Research Leader and Supervisory Research Hydraulic Engineer
Coleman, David L.	Physical Science Technician
Dahlquist, Gail H.	Biological Laboratory Technician
Dedrick, Allen R.	Laboratory Director and Supervisory Agricultural Engineer
Dierig, David A.	Research Geneticist (Plants)
Eastman, Lynnette	Biological Technician (Plants)
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary
Heckart, Donna J.	Secretary
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Jackson, Ray D.	Research Physicist
Johnson, Earl R.	Agricultural Research Technician (Plants) (Resigned 7-17-92)
Johnson, Stephanie M.	Biological Technician
Kimball, Bruce A.	Research Leader and Supervisory Soil Scientist
LaMorte, Robert L.	Civil Engineer
Lewis, Clarence L.	Machinist
Martinez, Juan M. R.	Agricultural Research Technician
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Programmer Analyst
Moran, M. Susan	Physical Scientist
Nakayama, Francis S.	Research Chemist
Padilla, John	Engineering Technician
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Powers, Donald E.	Physical Science Technician
Rasnick, Barbara A.	Physicial Science Technician
Replogle, John A.	Research Hydraulic Engineer
Rice, Robert C.	Agricultural Engineer
Rish, Shirley A.	Secretary
Rokey, Ric R.	Biological Technician
Salisbury, T. Lou	Office Automation Assistant
Seay, L. Susan	Publications Clerk
Seay, Ronald S.	Agricultural Research Technician
Thompson, Anson E.	Research Plant Geneticist
Wahlin, Brian T.	Civil Engineer
Wall, Gerard W.	Plant Physiologist
Woomer, E. Elizabeth	Secretary (Retired 2-3-92)

TEMPORARY EMPLOYEES

Anderson, Kim E.	Biological Aide
Bautista, Eduardo	Agricultural Engineer
Bhattacharya, N.	Plant Physiologist (Resigned 6-29-92)
Bertrand, Brian L.	Biological Aide (Resigned 8-22-92)
Eshelman, "Skip" T.	Physical Science Technician (Resigned 8-19-92)
Freitag, Laurel A.	Laboratory Helper
Gallagher, Daniel	Physical Science Aide
Garcia, Richard L.	Plant Physiologist
Graham, Barry G.	Computer Clerk
Henry, Douglas J.	Biological Aide (Resigned 4-21-92)
Higgins, John D., Jr.	Biological Aide
Holmwood, Beth A.	Biological Aide
Johnson, Michael S.	Physical Science Aide
Klassen, Matthew	Physical Science Aide
Klosterman, Evelyn M.	Biological Aide (Resigned 3-26-92)
Lacy, London P.	Biological Aide
Lazar, Bruce L.	Physical Science Aide
Macuiba, Andrew M.	Biological Aide (Resigned 12-12-92)
Newton, Anthony T.	Biological Aide
O'Brien, Carrie C.	Biological Aide
Pizmont, Ronald M.	Physical Science Aide (Resigned 1-17-92)
Pizzi, Judith A.	Biological Aide (Resigned 3-7-92)
Reaves, Matthew L.	Physical Science Aide
Rebman, Jon P.	Biological Technician
Renfrow, Roger R.	Biological Aide
Smith, Sue N.	Biological Aide (Resigned 6-26-92)
Strand, Robert J.	Engineering Aide
Strelkoff, Theodor S.	Research Hydraulic Engineer
Sunderman, Matthew D.	Biological Aide (Resigned 12-12-92)
Tozier, Emily	Physical Science Aide (Resigned 9-18-92)
Villalobos, Miguel A.	Biological Aide
Weber, Robin L.	Biological Aide (Resigned 4-21-92)
Wedin, Alan P.	Physical Science Technician

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INTEGRATED IRRIGATION SYSTEM WATER MANAGEMENT

MANAGEMENT IMPROVEMENT PROGRAM (MIP) FOR IRRIGATED AGRICULTURE[1]

A.R. Dedrick, Supervisory Agricultural Engineer;
A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
E. Bautista, Agricultural Engineer

PROBLEM: Improved water management is essential to a sustainable irrigated agriculture. Farmers, irrigation districts, and support organizations must interact in ways appropriate to long-term resource management, environmental protection, and social well-being. The Management Improvement Program (MIP) methodology, a management process not unlike those available to improve the performance of corporate organizations, is being applied to the business of irrigated agriculture in an effort to improve its overall profitability and sustainability. Because the technology transfer issues associated with strengthening irrigated agriculture are likely to be similar to those in other major areas of agriculture, it is anticipated that the MIP process will be widely applicable.

The purposes of this research are 1) to develop, apply, and evaluate the Management Improvement Program (MIP) methodology; and, 2) to consider how technology can be transferred effectively to the farmer and entities providing services to the farm, thus improving resource management and organizational effectiveness. Primary outcomes expected from the first purpose above--development, application, and evaluation of the MIP--are a generic MIP model and guidelines for its effective use, which may require several demonstration MIPs, and establishing institutional support to ensure the MIP's continued availability. A second set of outcomes, associated with methodology development, application, and evaluation, will include: (a) better understanding of the current status of, and problems and opportunities for improvement in, water resources management; (b) improved communication and collaboration among farmers, irrigation districts, and government agencies, resulting in strengthened and more effective working relationships; (c) identification, selection, and implementation of alternative actions to improve the operation and management of farm irrigation and water delivery systems; and (d) increased farmer profit/benefit.

The outcomes related to the second purpose above--transfer of the appropriate technology--include: (a) testing the effectiveness of technology transfer in an interorganizational, interdisciplinary setting; (b) providing a forum, and as appropriate, recommendations and/or direct input to test the MIP's effectiveness in responding to evolving relevant issues; and (c) using what is learned to strengthen other USWCL/ARS activities.

APPROACH: In December 1990, under the direction of the U. S. Water Conservation Laboratory, an Interagency Management Improvement Program (IMIP) was initiated. The collaborating agencies expressed an interest in the potential of the MIP to support improved irrigated agriculture productivity, profitability, and natural resource management. An oversight IMIP Coordinating Group (CG) was established (see 1991 Annual Research Report [ARR] for more information). In 1992, The University of Arizona College of Agriculture and Arizona Department of Agriculture joined the IMIP CG. The first major step in the overall assessment of the MIP was to be a demonstration application, currently being conducted in cooperation with the Maricopa-Stanfield Irrigation and Drainage District (MSIDD) in central Arizona. Efforts during 1991 and 1992 have focused mainly on this first demonstration, the MSIDD-Area MIP; the remainder of this report focuses primarily on that MIP.

Milestones in the MSIDD Area MIP during 1992 (see 1990 and 1991 ARRs for milestones during those years):

1) <u>Completion of the Diagnostic Analysis (DA), Phase I of the MIP</u>, included completing data collection and analysis; developing, reviewing, and finalizing the two-volume DA report; and linking to Phase II, the Management Planning Phase (MPP) of the MIP. Volumes I and II of the MSIDD-Area DA Report were published in March and July 1992, respectively.
2) <u>Part 1 (March-April) of the MPP</u> began with a preparation meeting on March 25 and closed with a planning review meeting on April 27. All organizations shown in Figure 1 are participants in the MSIDD-Area MIP MPP. The overall purpose of Part 1 activities was to support the MSIDD-area growers and the involved

[1] The Management Improvement Program Team (MIPT) includes Dedrick, Bautista, S. A. Rish (Secretary to the Director, USWCL), and consultants W. Clyma (MIP Specialist) and D. B. Levine (Management/Team-Building Specialist).

Organizational Teams in, first, building on and transforming the DA findings into their own shared understanding of the current performance of the area's irrigated agriculture and, then, in providing guidelines for the development of management plans to improve that performance. Key events in Part 1 included Workshop I, a four-day event, in which grower representatives and Organizational Teams developed (a) a shared understanding of each other's mission, (b) a shared understanding of current performance of irrigated agriculture in the MSIDD Area, and (c) general priorities for performance improvement; and Workshop II, a three-day event, in which organizational planning subteams established specific planning priorities. A significant outcome of Workshop II was the establishment of the MSIDD-Area Management Assistance Program (Table 1), a pilot interagency effort to support a limited number of growers in improving resource management, and therefore profitability, during the 1992 growing season. Also, a Water Costs and Assessment Committee was established to focus on high water cost and assessment issues associated with agriculture in the MSIDD area.

3) Part 2 (August 1992-March 1993) of the MPP was framed to support the MSIDD-area growers and involved organizations in developing a set of Management Plans whose implementation will effect changes deemed likely to improve the profitability and sustainability of MSIDD-area irrigated agriculture. Based on over 50 activities suggested by participants to MPP Parts 1 and 2, three MPP Planning Area (PA) workgroups were established (Table 2). Important activities for PA1 have centered on the establishment of an Interim Coordinating Group to provide ongoing coordination after formal completion of the MSIDD-Area MIP. PA2 has identified two main program thrusts: 1) Improved Irrigation Effectiveness, including irrigation design and management on-farm, and related water delivery services; and 2) Improved Cultural Practices, including soil conditioning, tillage, nutrient, and pesticide management. PA3 is focusing on water cost management and at present is providing a forum and input to support MSIDD's understanding of the issues involved in its negotiations with the Bureau of Reclamation (BOR), the Central Arizona Water Conservation District (CAWCD), and the Arizona Department of Water Resources (ADWR) to ensure that the Central Arizona Project remains financially and operationally viable.

FINDINGS: Findings related to the MSIDD-Area MIP include the identification of problem/opportunity areas for improvement, with the DA findings and DA-related understandings providing the basis for the comprehensive interorganizational/interdisciplinary planning now in progress. Some DA-based changes already have been or are being implemented. Coordination, communication, and collaboration have markedly improved or increased over the life of the MSIDD-Area MIP and must be recognized as major factors underlying the success of the MIP process. Also, overall MIP process model development and assessment are progressing satisfactorily.

INTERPRETATION: The interdisciplinary approach of the MIP process provides a rich and useful departure from traditional, single-disciplinary problem-solving and encompasses an understanding of real-world performance. The Planning Area activities have proven the findings to be accurate and conducive to planning, reflecting the interdisciplinary/interorganizational nature of most opportunities, and potentially generalizable elsewhere. The MIP process ("the model") is more fully understood, and the value of experiencing the process by which the MIP is carried out has been repeatedly expressed by the participants. Indicators of the utility of the MIP process are reflected by the high level of interest, involvement, and support shown by the participants, both growers and individuals from the involved organizations. Formal and informal discussions regarding use of the MIP process have been held with the Bureau of Reclamation, state organizations, The World Bank, and representatives from Turkey. Three papers based on the MIP have been presented at meetings during 1992.

FUTURE PLANS: The demonstration MIP will be continued in the MSIDD with Phase III, the Performance Improvement Phase (formerly Management Performance), scheduled to begin in Spring 1993. It is anticipated that the MSIDD-Area MIP will be completed by the end of 1993. In December 1992, an MIPT retreat was held to clarify the long-term direction of the overall (IMIP) program.

COOPERATORS: Cooperators in the MIP program include all entities listed in Table 2, as well as The University of Arizona College of Agriculture and Colorado State University. Funding has been provided by ARS, BOR, SCS, and the ADWR; in-kind contributions have been made by all involved.

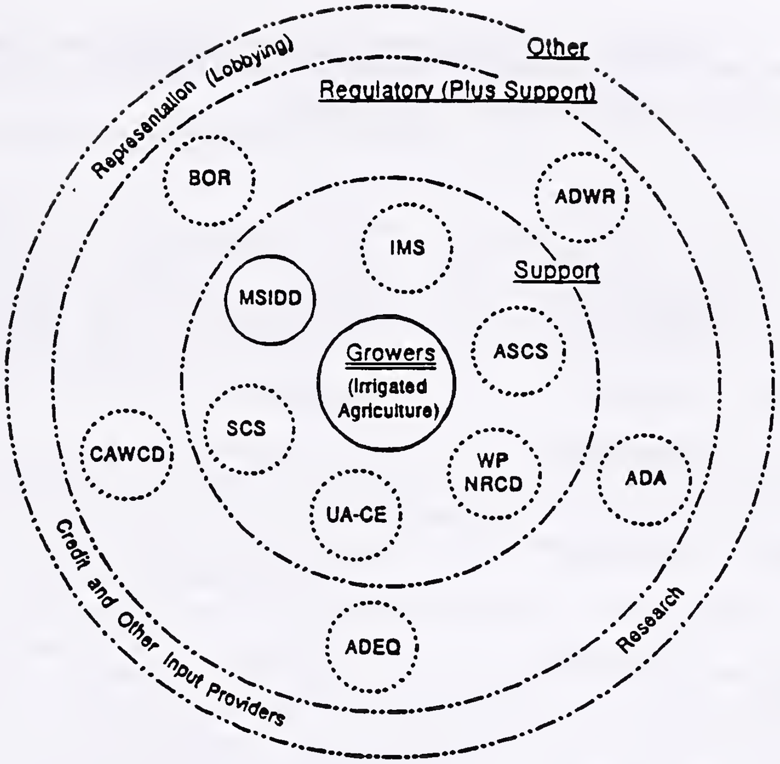


Figure 1. Schematic representation of entities involved in the demonstration MIP because of their potential to impact irrigated agriculture in the MSIDD area. Profitability and sustainability of irrigated agriculture are the focus of the MIP; therefore, growers are appropriately shown in the center. The solid circles around the MSIDD and Growers depict the entities that were studied in depth in the MSIDD area DA. The other organizations became fully involved during Phase II, the Management Planning Phase.

Table 1. MSIDD Area Management Assistance Program Team (MAPT) membership.[1]

REPRESENTATIVE	POSITION AND AGENCY
Ralph Ware, Chairman	Dist. Conservationist, Soil Conservation Service (SCS), Pinal County
Buddy Ekholt	Irrigation Management Service (IMS)
Rick Gibson	Extension Agent, Univ. Ariz. Coop. Ext. (UA-CE), Pinal County
Gary Sloan	Water Master, Maricopa-Stanfield Irrig. & Drain. Dist. (MSIDD)
Leonard Grewing	Chief of Operations, MSIDD
Monte Nevitt	County Director, Agr. Stab. and Cons. Ser. (ASCS), Pinal County
Gary Butler	Director, West Pinal Nat. Resource Cons. Dist. (WPNRCD)

[1]The Management Improvement Program Team of Dedrick, Levine, Clyma, and Rish assisted the MAPT.

Table 2. MSIDD Area Planning Area Workgroup membership. The planning areas are Planning Area 1--Overall Coordination and All Area Impact; Planning Area 2--On-Farm Profitability and Sustainability; and Planning Area 3--Water Costs, Assessments, and Related Concerns.

ENTITY	ICG (PA1)	PA2	PA3
Growers	Carlos Carranza Loren Pratt	Pat Murphree Dave Goldman	Bill Scott Dennis Nowlin
Soil Conser. Ser. (SCS)	Ralph Ware	Phil Jacquez	
Agr. Stab. and Conser. Ser. (ASCS)	Monte Nevitt[1]		
Univ. Ariz. Coop. Ext. (UA-CE)	Sam Stedman[1]	Ed [illegible]rtin	
West Pinal Nat. Resource Conser. Dist. (WPNRCD)	McD Hartman	Gary Butler	
Irrig. Mgmt. Ser. (IMS)	Buddy Ekholt	Buddy Ekholt	
Maricopa-Stanfield Irrig. and Drain. Dist. (MSIDD)	Van Tenney	Brian Betcher Gary Sloan	Van Tenney
Ariz. Dept. of Water Res. (ADWR)			Tom Carr
Pinal Active Mgmt. Area (ADWR-PAMA)	Dennis Kimberlin	Duncan Galusha	Randy Edmond
Ariz. Dept. of Envir. Qual. (ADEQ)		Andy Travers	
Central Ariz. Water Conser. Dist. (CAWCD)	Cliff Neal		Cliff Neal
Bureau of Reclamation (BOR)	Tom Burbey		Tom Burbey
Ariz. Dept. of Agr. (ADA)			John Hagen[1]

[1]Invited

IRRIGATION FLOW MEASUREMENT STUDIES

J.A. Replogle, Research Hydraulic Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: Measurement of flowing water continues to be a major tool for conserving water in irrigated agriculture through improved irrigation water management. Problems with flow rate devices include their relative complexity, required training level of field users, and economics of installation and operation. Other problems include pipeline flows that take their water from canals and can carry trash unsuitable for propeller meters. Yet a further problem involves sensing water surface by a reliable and accurate method that is compatible with data acquisition and control systems.

APPROACH: A selection of old measuring techniques with a view to updating them in the light of more recent understanding of fluid dynamics and advances in secondary instrumentation is being evaluated. A general approach to evaluating all measuring devices involves carefully constructed, or prepared, test items and the comparison of their flow rate with the discharge rate determined by a calibrated standard device, and further evaluating its general hydraulic behavior as predicted by hydraulic theory.

a) Venturi meters were fabricated from standard plastic pipe parts as shown in Figure 1 and calibrated against the Laboratory weigh tank system.

b) Multiple floats made of colored ice cubes and dyed popcorn were simultaneously dumped above a starting point in canals and timed over 100 feet of travel distance. The lead particle was timed in the field.

c) The Vane flow meter was configured to use a triangular blade, which is theoretically necessary for testing given the rectangular shape of the laboratory glass-sided channel. A force cell that is now commercially available was used to measure the torque about a vertical hinge line.

d) The Clausen Weir Rule has been in use in the Southwestern United States for over two decades. Its free flow characteristics were verified, and the theoretical basis that seemed to be used by its deceased developer was re-established. The submerged flow theory that must have been used for that application has not yet been determined.

e) Propeller meters for trash-filled flows were constructed by reversing the propeller on its shaft and attaching its nose to the downstream end of a special vane, or fin, that holds the propeller at the centerline of the particular pipe being monitored, Figure 4.

FINDINGS: a) The Venturi meter study is nearing completion. The basic construction for the final version of the plastic pipe Venturi is shown in Figure 1. Plastic pipe fittings of the kind usually used by the irrigation industry can be fashioned into suitable Venturi meters with an expected accuracy of $\pm$ 2%, not including the errors of the readout method. These constructions conform to expected Venturi meter behavior with a discharge coefficient about 2% to 5% lower than "standard" types. The basic laboratory data that establishes the discharge coefficient and the pressure losses were presented in a paper at a July conference.

b) Analysis of data sets for six canals of widely varied sizes supports the rationale that a reasonably well defined relationship involving absolute roughness and the most rapid surface velocity filament does exist. Figure 2 indicates a linear relationship between the ratio of maximum surface velocity and the average channel velocity (y-axis), and the ratio of the absolute roughness and the hydraulic radius (x-axis).

c) The triangular configuration indicates discharge per unit width without specific reference to flow depth. The linearity of the output readings from the force cell is excellent, but the range of the particular cell is too large. A smaller ranged cell is being obtained.

d) The most apparent feature of the Weir Rule is how it averts the necessity of dealing with a velocity of approach. The form of the equation on which it appears to be based is in terms of total head at the weir overfall, which already includes the velocity of approach adjustments. Figure 3 shows results from laboratory tests on a 1.23-m-wide sharp-crested weir.

e) A new type of electronic, waterproof, bicycle speedometer was adapted to the reversed propeller shaft, and calibrations were made in the laboratory. Basically, it is hung by the "nose" onto the downstream side of a sloping vane attached to the pipe top, Figure 4. It offers little chance to catch debris. The worst situation encountered in

the laboratory tests was strings and ribbons about 1.5 m or more in length. Preliminary field testing showed that it is resistant to clogging, and that it appears to calibrate reliably.

f) A patent application was filed with the U.S. Patent Office in October 1991 for a specially arranged adjustable flume. It was issued as Patent No. 5,156,489 on October 20, 1992. The basic patent idea will be applied to leaf gates that are described elsewhere.

INTERPRETATION: a) The most important construction factor for plastic Venturi meters is the fabrication of the pressure taps. They should be drilled with appropriate backing blocks to reduce burrs and with a guide to assure that they are perpendicular to the pipe wall. Costs are about $120 US (1992) for the pipe and fittings, plus about 2 hours of labor, per meter. Individual calibration is not required. A Venturi meter construction and readout manometer was demonstrated near Springerville, Arizona, for the Soil Conservation Service to copy for other field installations.

b) Based on the hydraulic radius, R_h, and reasonable handbook values for channel roughness, n, which can be converted to absolute roughness, K_r, the ratio of average channel velocity to maximum surface velocity, v_a/v_r, can be established as a function of K_r. This appears to reduce the uncertainty in the float method to a more acceptable $\pm 5\%$ value. Previous estimates of uncertainty were as much as $\pm 15\%$.

c) Properly shaped vanes, or blades, used as a type of fluid drag body, can indicate flow rate per unit width without specific knowledge of flow depth if the horizontal force can be measured. Simple triangles measure rectangular channels if rotational force is monitored about a vertical axis. Other channel shapes require more complicated shapes. Several mechanical innovations allow portability and nonsensitivity to precise vertical alignment.

d) Properly used and on an appropriate sharp weir crest, the weir rule functions satisfactorily for many irrigation measuring activities. Against weighed discharge rate, it is about 1% to 2% too high.

e) A propeller meter configuration and readout method has been devised that deviates from previous concepts being manufactured and may lead to a general purpose, trash-resistant, propeller meter adaptable to many pipe sizes, and with a readout method that will be economical, reliable, and capable of indicating flow rate and total volume of irrigation water delivered.

FUTURE PLANS: a) The basic laboratory data that established the discharge coefficient and the pressure losses in plastic pipe Venturi meters that were presented in a paper at a July conference, have been extended to a full length manuscript soon to be submitted for review and publication. As a check, tests on another size is planned.

b) The data sets on canals have recently been extended. These data will be studied before additional field tests are designed.

c) The force meter will be further laboratory evaluated for its expected functions, using a smaller force cell. Attempts to extend it to serve as a weir-overfall measuring device will be investigated. There is preliminary evidence that it might be able to function as an advanced "weir rule."

d) The submerged flow functions of the weir ruler will continue to be investigated and a suitable theoretical basis sought to better understand the limitations and possible extensions of the method.

e) The propeller meter will be installed into a 0.76 m (30 inch) irrigation delivery pipeline to evaluate field maintenance and operational lifetime expectations.

f) A bubble-curtain flow measuring technique that has field utility, particularly for otherwise difficult-to-measure earthen channels will be investigated. Preliminary designs for simple equipment has been developed for field use and will be built.

COOPERATORS: There are no formal cooperators on these projects. Parties that have expressed specific interest include the Soil Conservation Service, various irrigation districts, and irrigation consultants.

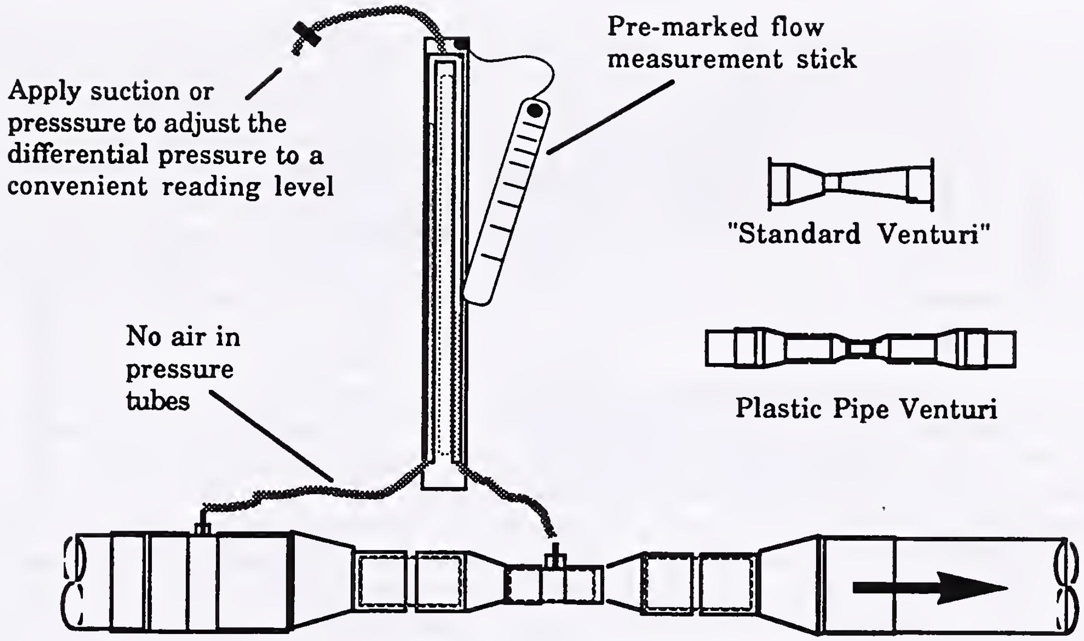


Figure 1. Configuration installed in the field.

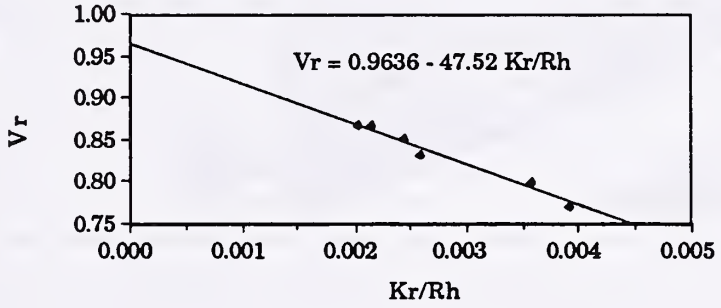


Figure 2. Results for six canals.

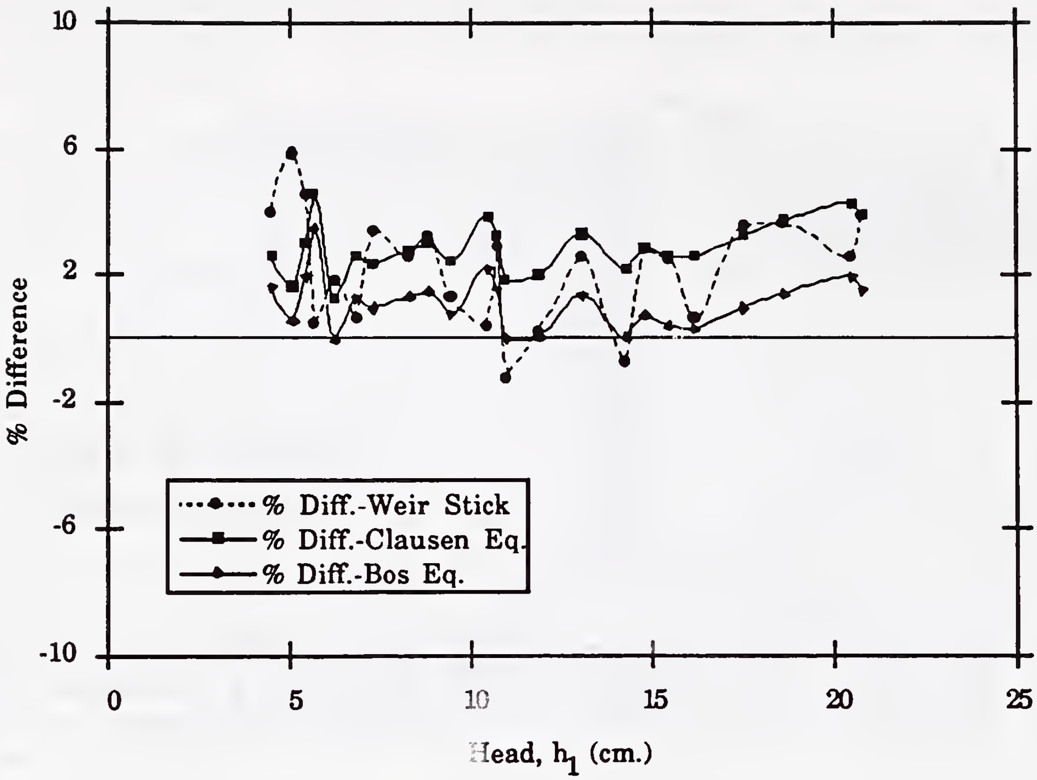


Figure 3. Differences from weighed discharge of weirstick and weir equations.

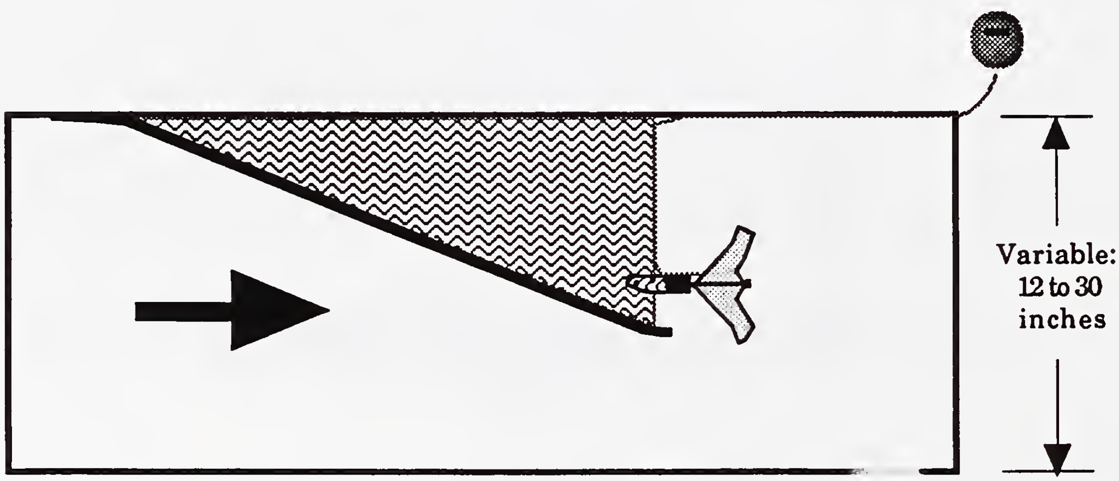


Figure 4. Modified propeller meter that resists debris clogging.

HIGH-FREQUENCY LEVEL BASIN IRRIGATION FOR COTTON

D.J. Hunsaker, Agricultural Engineer;
A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
W.L. Alexander, Agronomist

PROBLEM: Cotton is one of the most important economic crops grown in the arid southwestern United States. In Arizona, where cotton is the principal crop, irrigation is accomplished predominantly with surface methods. Most surface irrigation systems are designed and managed to minimize irrigation frequency, resulting in a large volume of water being applied during each irrigation. This type of irrigation management [low-frequency, large-volume (LF-LV)] does have its advantages in terms of minimizing labor, energy, and costs, and maximizing lengths of run.

However, cotton, like many crops, can be highly susceptible to water stress during fruiting, which can adversely affect yields. Supplying water frequently during the fruiting period tends to "protect" the water and nutrient transport capabilities of the root system while supplies are diverted to the fruit. Yet, traditional surface irrigation scheduled at long intervals practically assures some degree of water stress during the fruiting period. This may be the primary reason field studies often show that high-frequency micro irrigation (drip or trickle) produces higher yields and water-use efficiencies for cotton over flood or furrow irrigation.

Recent studies (Bucks et al., 1988; Radin et al., 1992) have also demonstrated that high-frequency level basin irrigation of cotton is also advantageous over the conventional low-frequency level basin irrigation. The results of Radin et al. (1992) are of particular interest. They demonstrated that much of the growth and yield benefits associated with daily drip irrigation could be achieved by simply increasing the frequency of level basin irrigation only during a 3-4 week period coinciding with peak fruiting. Thus, some of the more recent work suggests that a high-frequency, small-volume (HF-SV) level basin irrigation scheme may realize a significant improvement in crop environment and yield over LF-LV irrigation. However, the level basins used in the above studies were small, plot-size basins. The key to implementing high-frequency irrigation management for cotton with level basin irrigation lies in the success at the farm-scale level.

The objectives of this project are to evaluate a level basin design procedure for high-frequency, small-volume irrigation and to evaluate the economic feasibility of this irrigation regime for growing cotton in the southwestern United States.

APPROACH: A level basin design procedure for HF-SV irrigation will be evaluated in a detailed analysis of a specific field site at The University of Arizona, Maricopa Agricultural Center (MAC). A large, precision leveled site having moderate soil intake rates will be selected at MAC to conduct the field experiments. After constructing conventional cotton beds (1.0-m spacing), a series of preliminary studies will be implemented to evaluate and compare field conditions affecting basin distribution uniformities when HF-SV and LF-LV water applications are made. Some of the key factors which will be evaluated in these studies include 1) the variation in furrow intake rates, surface roughness and furrow advance rates during the season as a function of irrigation frequency, 2) the limit on application depth as intake rates and flow resistance conditions change during the season and 3) the effect of soil variability and surface irregularities on the uniformity of water applied when applications are small and large.

The results from the preliminary studies will be used as guidelines to develop design procedures which will allow management to first choose a desired cotton irrigation schedule and then, to select an efficient design to meet this schedule. Design procedures for three alternative irrigation schedules will be developed: 1) HF-SV irrigation during the entire growing season, 2) LF-LV irrigation during the entire season, and 3) a combination irrigation schedule of HF-SV during the peak fruiting period of cotton and LF-LV at other times in the season. The current version of the surface irrigation simulation program, SRFR, will be used to develop design charts for each irrigation event of a schedule, showing the effect on distribution uniformity for combinations of application depth and field length (available flow rate will be that available at the field site). The infiltration and roughness parameters will be partitioned for each irrigation event according to the results from the preliminary field studies. The charts for a given irrigation schedule will then be used as guides to selecting an appropriate basin design for the field site to attain acceptable seasonal distribution uniformities (efficiencies).

The three design/management systems will also be installed and replicated on the field site to test their performance for growing cotton over at least two seasons. An economic analysis will then be made to compare the profitability of the alternative systems, considering such factors as yield revenues, water, energy and chemical costs, and other costs associated with land preparation, labor, and machinery operations.

INTERPRETATION: This research will demonstrate whether or not high-frequency, small-volume level basin irrigation is feasible from both a practical and economic standpoint. The extensive field measurements will provide information on level basin design limitations when small applications are attempted. Performance of the system, and yield and water use data will be obtained in field units closer in scale to those used by growers in the region. However, it is reasonable to assume that the high-frequency system will still require smaller field units than those used by commercial growers. In addition, high-frequency irrigation will likely be more expensive to operate as well. Thus, management considerations and higher costs of operation would need to be offset by increased yields with the high-frequency irrigation management.

COOPERATORS: Dr. D.D. Fangmeier, Department of Agricultural and Biosystems Engineering, The University of Arizona.

REFERENCES:

Bucks, D.A., Allen, S.G., Roth, R.L. and B.R. Gardner, 1988. Short staple cotton under micro and level-basin irrigation methods. Irrig. Sci. 9:161-176.

Radin, J.W., Reaves, L.L., Mauney, J.R. and O.F. French, 1992. Yield enhancement in cotton by frequent irrigations during fruiting. Agron. J. 84:551-557.

MODIFIED LEAF GATES FOR CANAL CONTROL AND MEASUREMENT

J.A. Replogle, Research Hydraulic Engineer; and B.T. Wahlin, Civil Engineer

PROBLEM: Leaf gates, sometimes called overfall gates, are being used in the Imperial Irrigation District (IID) and in many other places, such as a floodway from the Salt River Project (SRP) canals. These gates are built by a company in Fresno, CA. Their general configuration is shown in Figure 1. Advantages include the ability to obstruct, or control, flow from essentially no interference to complete shut-off. A disadvantage is the high forces required to raise the gate, and edge seals, which effectively limit its application to rectangular channel sections.

The gate is widely used in the control mode when water level is the desired criterion. Sometimes both control and flow rate are desired. In this capacity, the leaf gate would be monitored for depth of flow over its crest, and this value used to determine discharge. The control aspect would imply that the water source is a lake or a canal capable of responding to control of the backwater effects that would be required to discharge a fixed flow rate. This use as an overflow measuring weir with a variable sloping front face appears to be valid if properly determined coefficients can be verified for use in the sharp-crested weir equation of the form

$$Q = C_d \, b \, \sqrt{2g} \, h^{1.5}$$

in which C_d = discharge coefficient; b = the width of the weir; g = gravitational constant; and h = the depth of flow measured upstream and referenced to the top, or overfall edge, of the weir plate. A rough set of discharge coefficients is offered by the manufacturer with a note of reservation. These coefficients varied from those for a vertical sharp-crested weir by as much as 40% at the low discharge ranges. While differences are to be expected, these are larger than anticipated.

For depth control purposes only, crest ventilation is not required, but for using this device as a measuring weir the downstream side of the weir plate must be ventilated. This means that the downstream water surface should be about 2 inches below the overspill crest. This also means that the downstream channel cannot be used very near to its full flow capacity.

APPROACH: The uncertainty of the discharge coefficient is being addressed by directly calibrating a generic leaf gate that we constructed using a 6 mm thick aluminum plate. The plate is fitted into a glass-sided laboratory channel 1.23 m wide by 0.6 m deep. The leaf-gate blade itself is the same width and is also 0.6 deep. The hoisting constraints and other factors limited the movement of this weir through a narrow range from about 23° to 39°. The lower angle is actually limited by the water level in the downstream channel (Figure 1), that interferes with proper weir crest ventilation.

A possibility for averting the need to provide a ventilated crest is to convert the device from a sharp-crested weir to a broad-crested weir. We are testing this concept, using a construction similar to that shown in Figure 2. This type of weir requires that the upstream and downstream water surfaces be about 15% different as referenced to the top of the weir crest. This should allow most of the downstream channel depth to be used. This should also permit, within limits, the controlling of upstream channel depth, while passing a required flow rate, or with automation, a variable flow rate.

All flow rates were determined with the laboratory weigh tank system accurate to $\pm 0.1\%$. The main errors were bypass leakage due to inability to completely seal the edges of the weir and leakage at the hinge joint. Sliding rubber seals were tried at first, but errors within detection limits of the system were occurring. Finally, we silicone sealed each position during the testing to stabilize results.

FINDINGS: Figure 3 shows the data points that included tests where seepage was suspected after the data were carefully analyzed. Figure 4 shows retesting after seepage was positively controlled using silicone caulking on all edges after the weir was positioned to a particular angle. This stabilized the results to a narrower limit and slightly increased the average determined C_d. The results to date, as shown in Figure 5, are essentially a straight line that does not differ a great deal in shape from that published in standard texts for 90° sharp-crested weirs, but which is slightly larger.

INTERPRETATION: One would expect that these results could be compared to the limiting case of the vertical weir. For a fixed discharge rate and weir crest elevation, one could reason that sloping the upstream face would streamline the flow and lower the upstream water depth, in effect requiring a larger discharge coefficient to calculate the same flow rate. Thus, the results of Figure 5 are as expected. However, if one closely examines the data set for the USWCL tests shown in Figure 5 at a larger scale (not shown), there is a slight trend in apparently the wrong direction, with increasing angle. The narrow range of angles available for testing does not assure that the trend really persists, or that it may not reverse about above 45°. This question cannot be answered at this time.

FUTURE PLANS: A contract to study a commercial version of the leaf gate is expected to start in January 1993. The objectives of that study are to verify or modify the published hydraulic behavior and the calibration as a measuring device, and to evaluate methods of improving the usable flow range of leaf gates used as both flow control and measuring devices.

COOPERATORS: UMA Engineering, Imperial Irrigation District, Armtec, Inc.

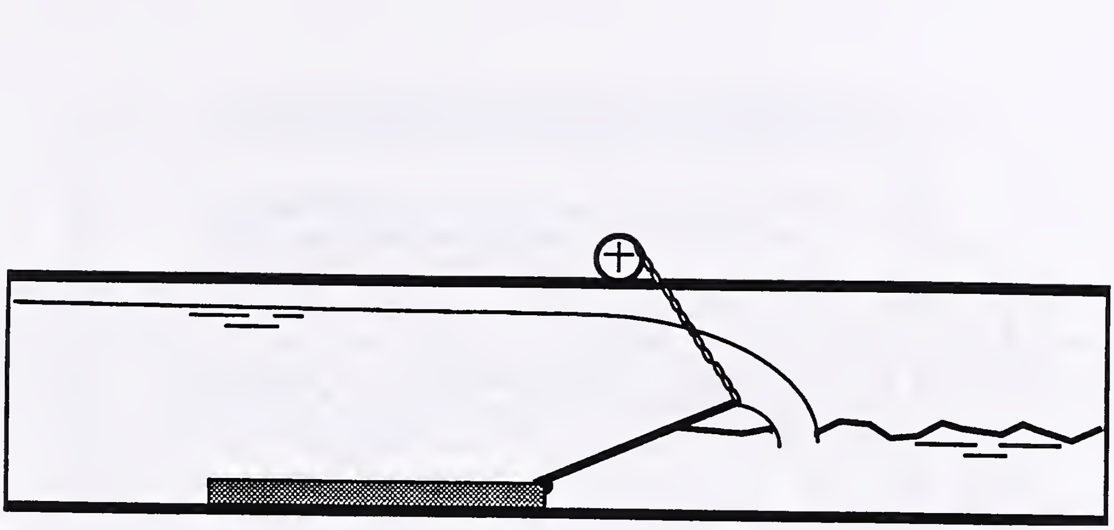


Figure 1. General configuration for a leaf gate.

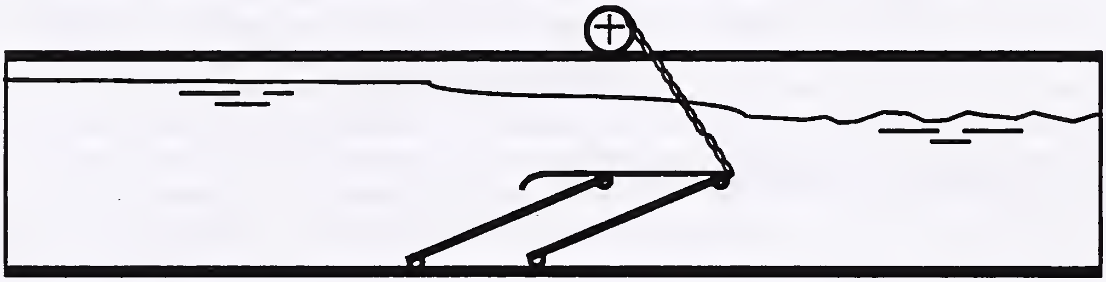


Figure 2. A proposed modification to a leaf gate to improve flow measuring ability.

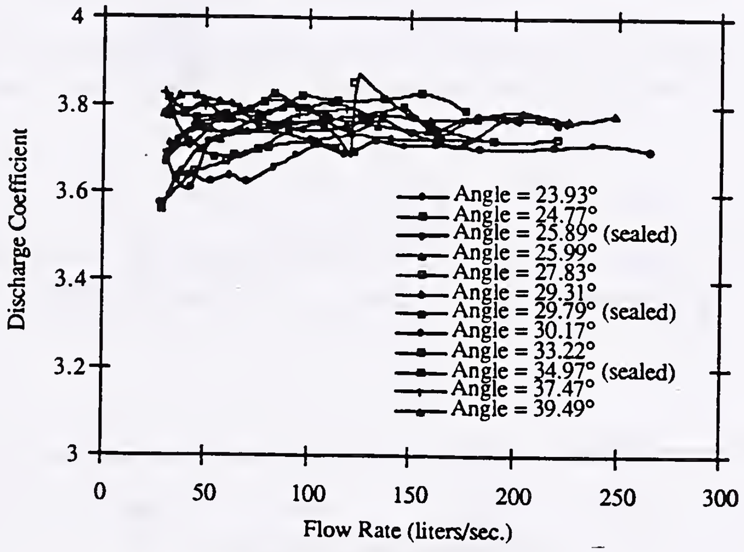


Figure 3. All tests, including those suspected of having some leakage.

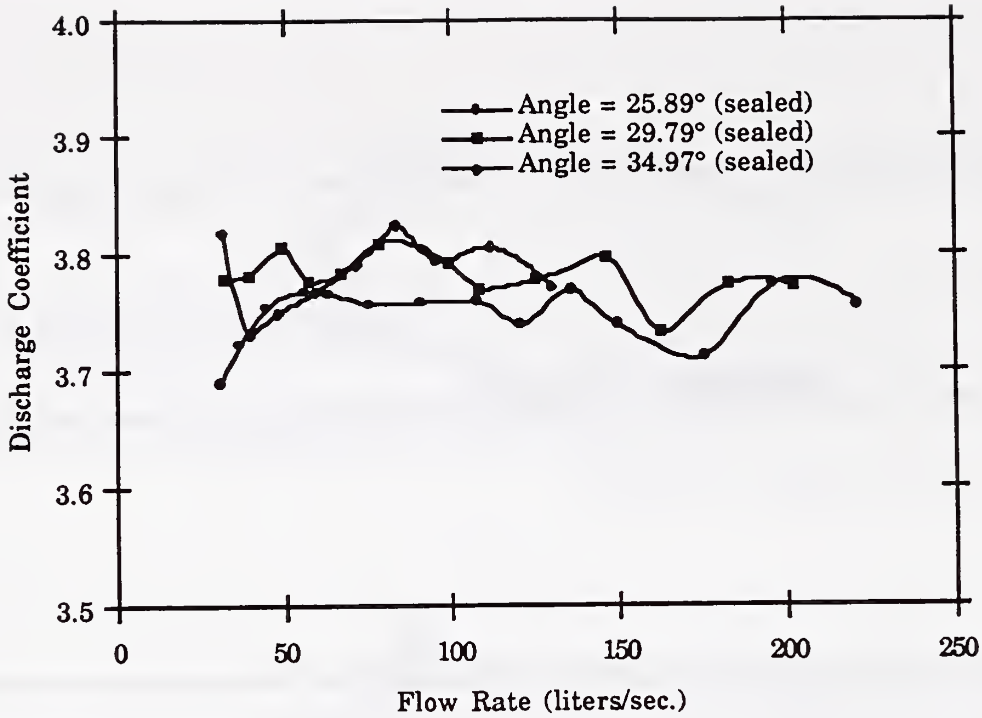


Figure 4. Tests with positive sealing against leakage.

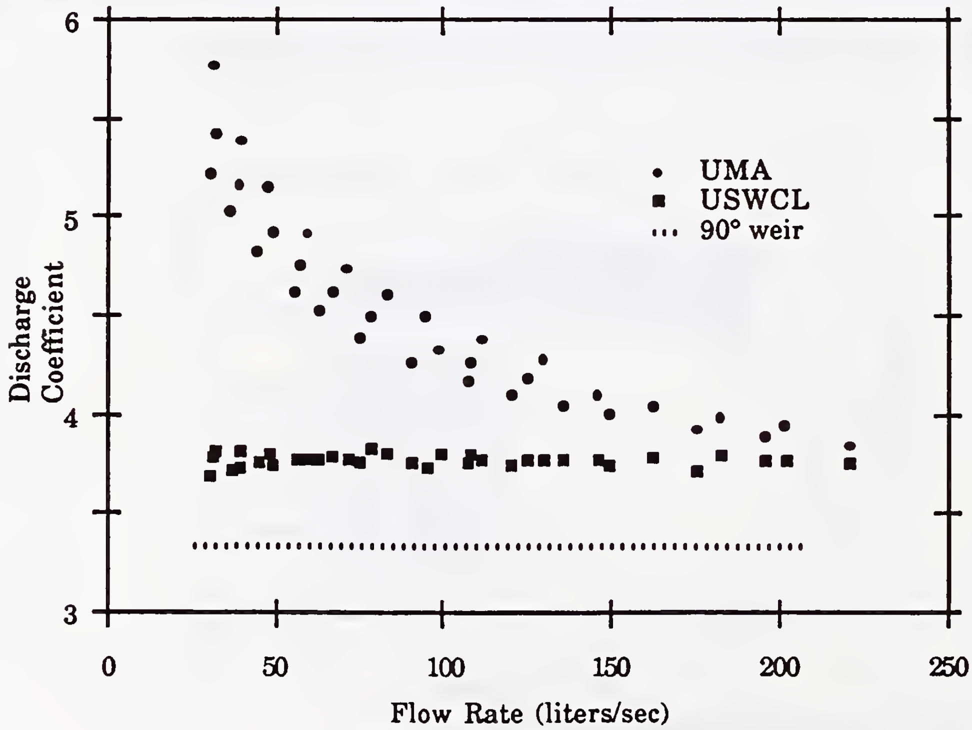


Figure 5. Comparison of leaf gate with manufacturer's equation and standard weir.

SOFTWARE FOR DESIGN AND CALIBRATION OF LONG-THROATED MEASURING FLUMES

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
J.A. Replogle, Research Hydraulic Engineer

PROBLEM: Flow measurement in irrigated agriculture continues to be a difficult problem. Flow measurements are frequently inaccurate, and structures are often improperly installed. Over the last decade, the long-throated flume has been developed as a very useful tool for improving water measurement in irrigation canals. One of the advantages of this device is that it can be custom designed for each installation, thus better meeting the needs of the measurement site. This can be a disadvantage in that it gives the user so much flexibility that an optimum structure may not be selected.

A computer program, FLUME, has been available since 1987, for the calibration of these flumes. It is not very user friendly, as users frequently make errors in data input, and laboratory personnel spend a significant amount of time answering user questions. Thus, there is a need for a more user friendly flume program that can aid the user in design of these flumes.

APPROACH: A menu-driven program, FLUME3.0, is being developed to aid in the design and calibration of long-throated flumes for irrigation canals and natural channels. The program will include design procedures developed over the last few years. The user will input the conditions of the canal and select the type of contraction desired. Then the program will come up with a structure that meets the channel conditions. The program also has graphic data input which shows the flume profile and cross sections so that, when the user enters flume dimensions, the changes can be viewed immediately. This should greatly reduce the chance of user error. A database of flume designs and calibration tables is also provided. The project is being sponsored by the International Institute for Land Reclamation and Improvement (ILRI), Wageningen, The Netherlands. A software programmer from Wageningen is under contract to ILRI to write the menu-driven program.

FINDINGS: The main parts of the program have been written, and a near-final version has been completed. The design routines were reprogrammed, tested and debugged. The program has been demonstrated to users and is currently under review. A manual describing the program has been written and will be published by ILRI. It should be available for distribution by early 1993.

INTERPRETATIONS: This program should help the transfer of this technology to users in a very effective manner. It will make these flumes an even more valuable tool for improving water management in irrigated agriculture.

FUTURE PLANS: Completion and maintenance on the computer program FLUME3.0.

COOPERATORS: M.G. Bos, International Institute for Land Reclamation and Improvement; and J.M. Groenestein, Groenestein and Borst, Ltd.

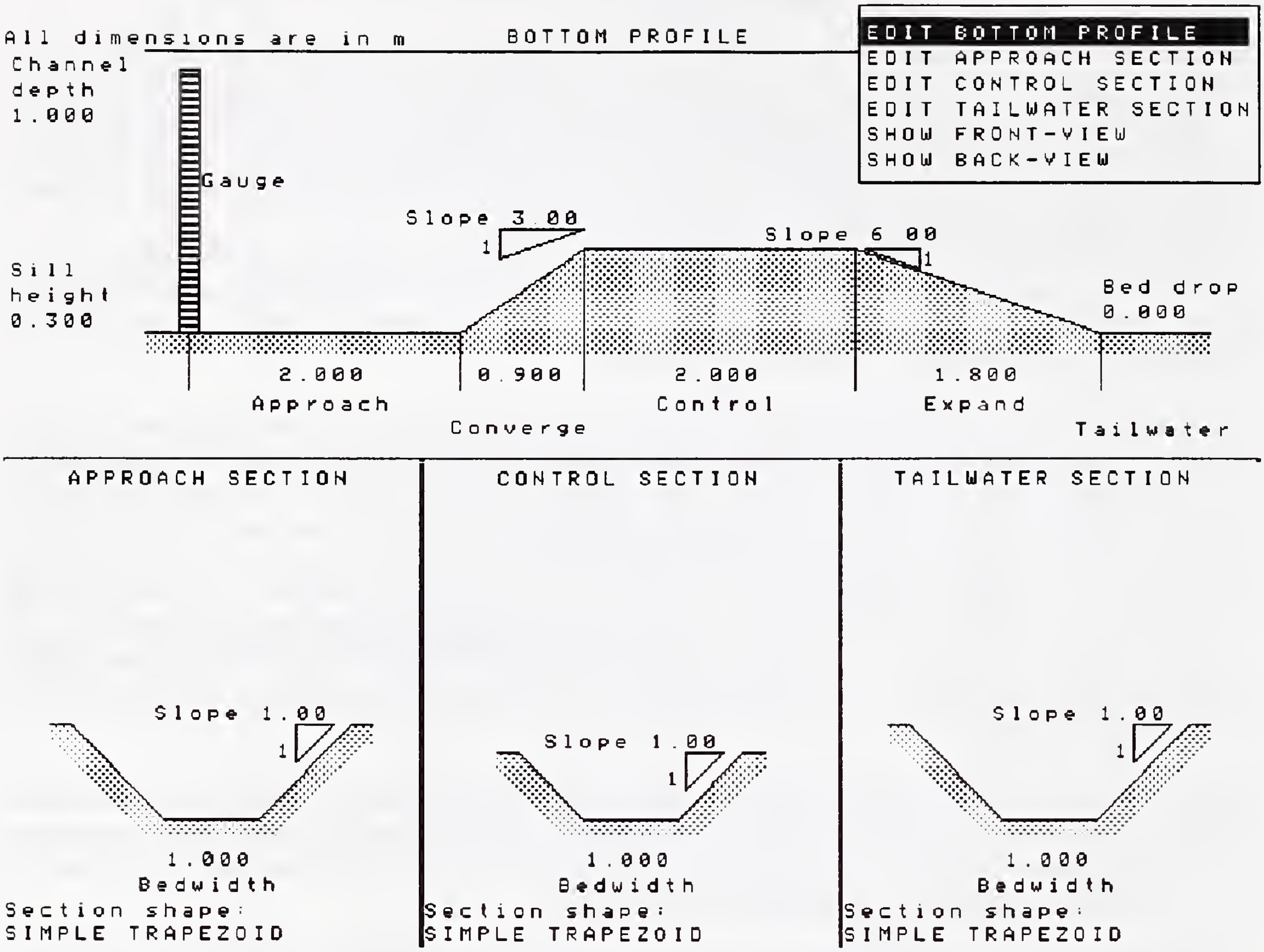


Figure 1. Graphics data entry screen for default flume.

```
User : Clemmens/Bos/Replogle          Report made on: November 20, 1992
Flume: Phoenix , example structure used in manual                 Version  3
                       EVALUATION OF FLUME DESIGN

GENERAL RESULT : Design is acceptable.     2 lines of error/warning text.
                 Headloss design aims are not fully met

              EVALUATION OF FLUME DESIGN FOR EACH DESIGN CRITERION

Ok.     Freeboard at Qmax.:    Actual=0.356 m    Minimum=0.094 m

Ok.     Head at Qmax.:         Actual=0.469 m    Minimum for accuracy=0.235 m

Ok.     Head at Qmin.:         Actual=0.100 m    Minimum for accuracy=0.099 m

Ok.     Tailwaterdepth Qmax.: Actual=0.844 m    Maximum allowed=0.858 m

Ok.     Tailwaterdepth Qmin.: Actual=0.109 m    Maximum allowed=0.507 m

Ok.     Froude nr. at Qmax.:  Actual=0.315      Maximum= 0.500

                      ADVICE, WARNINGS AND ERROR MESSAGES

Headloss design aims are not met.
Too much contraction in initial control section shape

                             RESULTING STRUCTURE.

Sill Height = 0.425 m
CONTROL SECTION DATA
Section shape = SIMPLE TRAPEZOID
Bedwidth = 1.850 m              Channel side slope =  1.00:1

                              DESIGN STRATEGY.

Headloss design aim: Minimize headloss
Contraction change strategy: Vary height of sill

                             DESIGN CRITERIA.

Type of structure: Stationary crest.
Freeboard design criterion: Percentage of head over sill = 20 %
Allowable discharge measurement errors for a single measurement:
  At minimum discharge:  8.00 %.    At maximum discharge:  4.00 %
Head detection method: Staff in still Fr=0.2  Readout precision: 0.005000 m
Design discharges and associated tailwater levels:
  Minimum discharge=  0.100 m3/s    Minimum tailwater level=  0.109 m
  Maximum discharge=  1.300 m3/s    Maximum tailwater level=  0.844 m
  Values derived using: 2 Q-H measurements
=== Use cursor keys, PgUp, PgDn, etc. to view whole text ===
```

Figure 2. FLUME design results screen.

IRRIGATION CANAL HYDRAULICS AND CONTROLS

A.J. Clemmens, Supervisory Research Hydraulic Engineer; and
T.S. Strelkoff, Research Hydraulic Engineer

PROBLEM: Surface-irrigation efficiency can most easily achieve high levels when the supply canals have been designed and are operated in a way to supply the necessary water at the right time to each of the users of the resource. In present systems, the possibility of meeting the canal-delivery requirements for efficient demand irrigation is not assured. The operation of gates and pumps in a canal system produces waves which transmit the effects of these operations throughout the system at a speed not much in excess of water velocity. The total effect at any location is the combined result of these waves, transformed during their travel, that arrive there from their points of origin. Numerical simulation of the unsteady flow encountered in irrigation canals allows predicting the results of given physical designs and management procedures.

As irrigation canal systems become more responsible to farm demands, changes in flow occur more frequently, causing unsteady flow throughout the system. Even large canal systems with rigid delivery policies which supposedly operate under steady flow often have unsteady flow for long periods of time. Most canal systems operate with manual upstream control. Here a constant water level at an offtake is used to keep delivery flow rates constant. The disadvantage of this system is that all flow errors end up at the tail end of the system. In large canals, supervisory control systems are used to adjust volumes in intermediate pools to keep differences between inflow and outflow more evenly distributed in the system, or simply stored until a balance is achieved. Smaller canals with insufficient storage need more precise downstream control methods than are currently available.

Many computer models of unsteady canal flow have been built in the last twenty years, some very complex and expensive, designed to model very complicated systems. Proprietary code is not readily accessed for modification to reflect new operating conditions or for incorporation into optimization routines. Some models, adopted by agencies and associated with years of experience, are reliable except when, physically, a hydraulic bore forms. Only rough, rule-of-thumb means are presently available for judging bore formation; use of an unsuitable model for simulation of these cases leads to incorrect results, not necessarily identifiable.

The objective of this research is to develop tools for the improved operation of irrigation canal networks, more specifically, to improve canal control algorithms, improve predictive capabilities of unsteady flow simulation programs, improve manual operating techniques, and improve local, automatic gate controllers.

APPROACH: Advances in control engineering have not been fully applied to irrigation canal downstream control. A few downstream control techniques are in use, but they have not been fully tested to determine their limitations. To aid in the evaluation of existing techniques and development of new ones, data will be collected on a few canals which may be difficult to control with existing methods. Further, we will collaborate with canal-control experts to assess various methods for automatic feedback control and assist in the implementation of these methods on these test canals. Canals within the Maricopa Stanfield Irrigation and Drainage District (MSIDD) will be studied, because they have the hardware available to automatically control gates at all check structures within lateral canals.

A simple model containing essential features of a controlled canal can be used to answer generic questions regarding mathematical simulation of unsteady open-channel flow and hypothetical questions about canal flow in general. The issue of bore formation can be studied most reliably with a model based on the method of characteristics in a technique that allows both families of characteristics to remain continuous. This technique is not the most efficient one for general use, so a suitable model would allow substitution of one approach for another. The current plan is to provide one subroutine based on the method of characteristics with construction of the full characteristic grid and another based on mass and momentum conservation applied to a grid based on lines of constant time and space.

FINDINGS: Data were collected for a 24-hour period on MSIDD canal WM. Much of the data contained too much random error to observe the effects we wanted to examine. The data collected were used to generate input into CANALCAD, an unsteady flow program. The results of CANALCAD were then used to look at the influence

of unsteady flow in the canal upon changes in delivery flows. These preliminary results were presented at a workshop in Montpellier, France, hosted by CEMAGREF.

The generic model of bores was developed and tested. It was found that canal length does not influence bore formation. In short canals, bores will form in the reflected waves, rather than in the initial advancing wave. Bore formation causes characteristics-based unsteady flow solutions to yield multiple, incorrect values. Other nonconservative schemes yield subtly incorrect values. A simple expression was developed to determine whether or not a bore will form as the result of an increase in inflow.

INTERPRETATION: Unsteady flow models are an important tool for evaluating canal operations and control methods. Some conditions under which a bore forms can be predicted and unsteady flow simulation programs modified to notify the user of this condition, so that it can be avoided.

FUTURE PLANS: Additional data will be collected on MSIDD canals in order to develop example problems for the development of canal control algorithms. These examples will be used to test various canal control algorithms and to help guide a new ASCE task committee on canal control algorithms.

COOPERATORS: Gary Sloan, MSIDD; Pascal Kosuth, CEMAGREF; Charles Burt, California Polytechnic; Wytze Schuurmans, Delft Hydraulics; Jam Schuurmans, Delft University of Technology; John Parrish, Utah State University; Mohan Reddy, University of Wyoming.

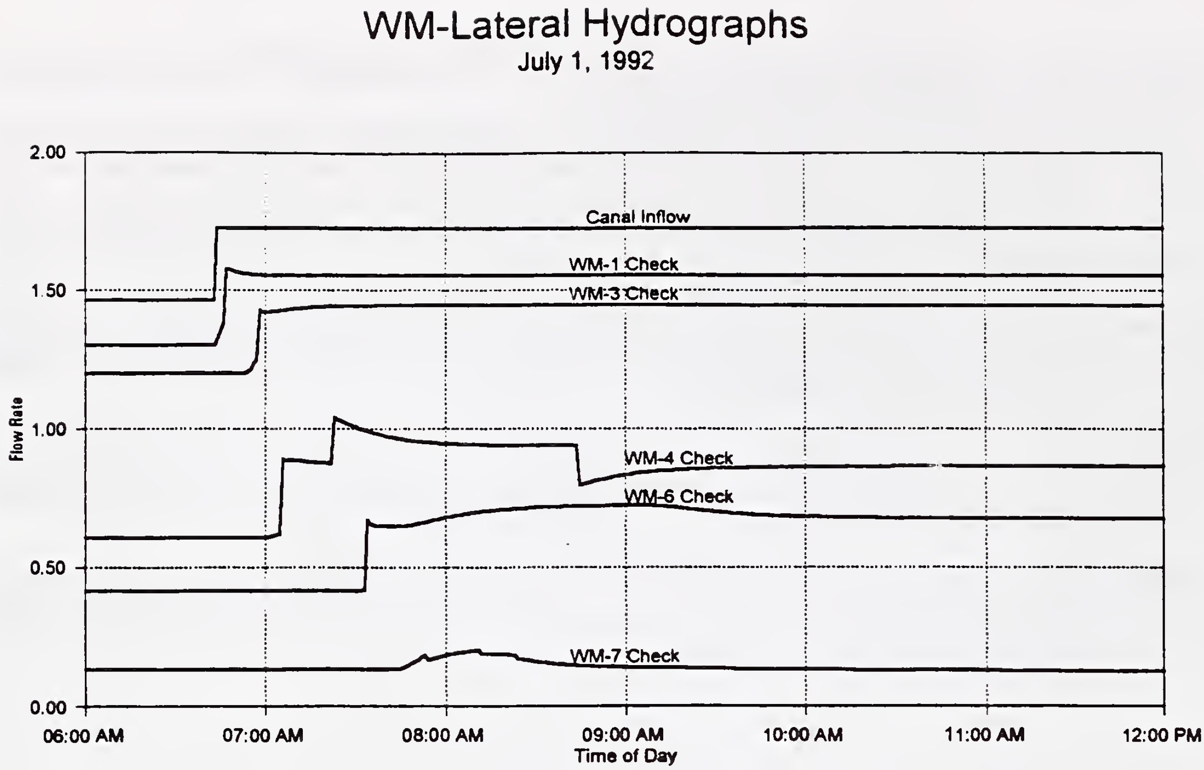


Figure 1. Canal WM: Calculated Flow rates (m^3/s) through check gates for a step change in inflow.

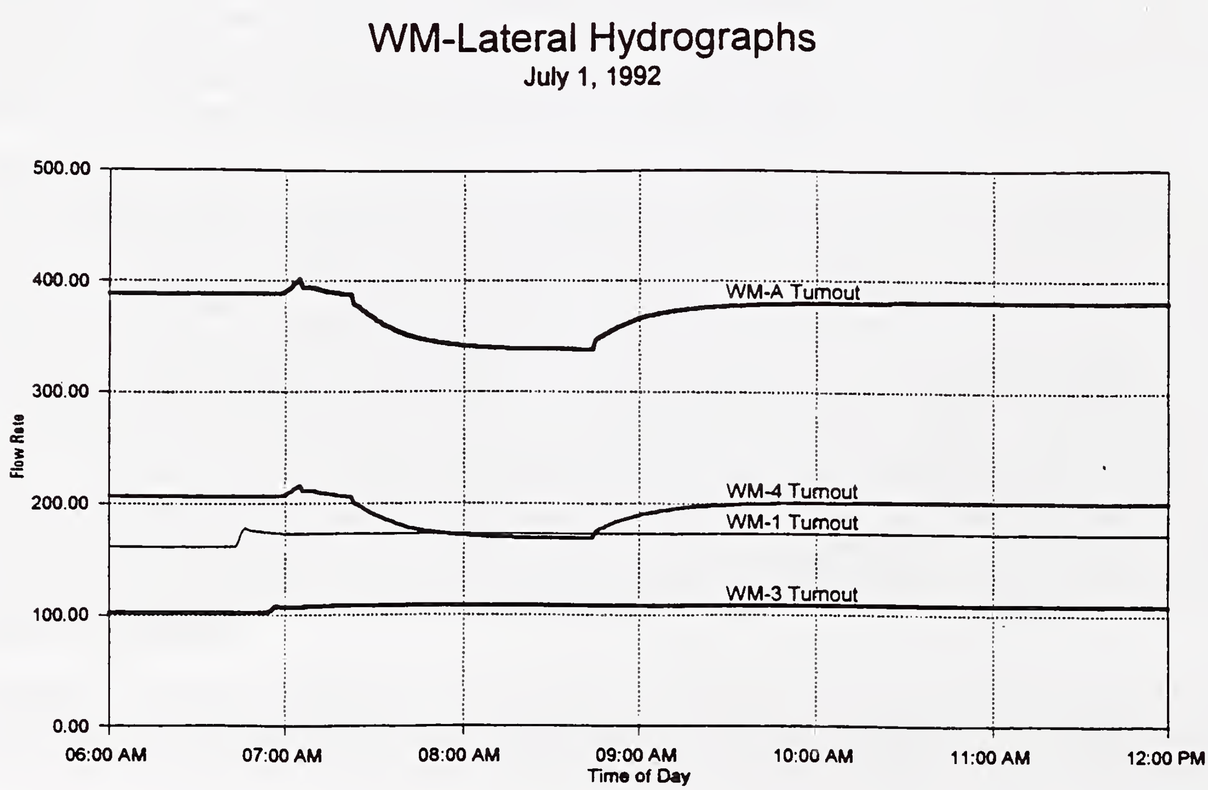


Figure 2. Canal WM: Calculated turnout flow rates (ℓ/s) for upstream part of canal.

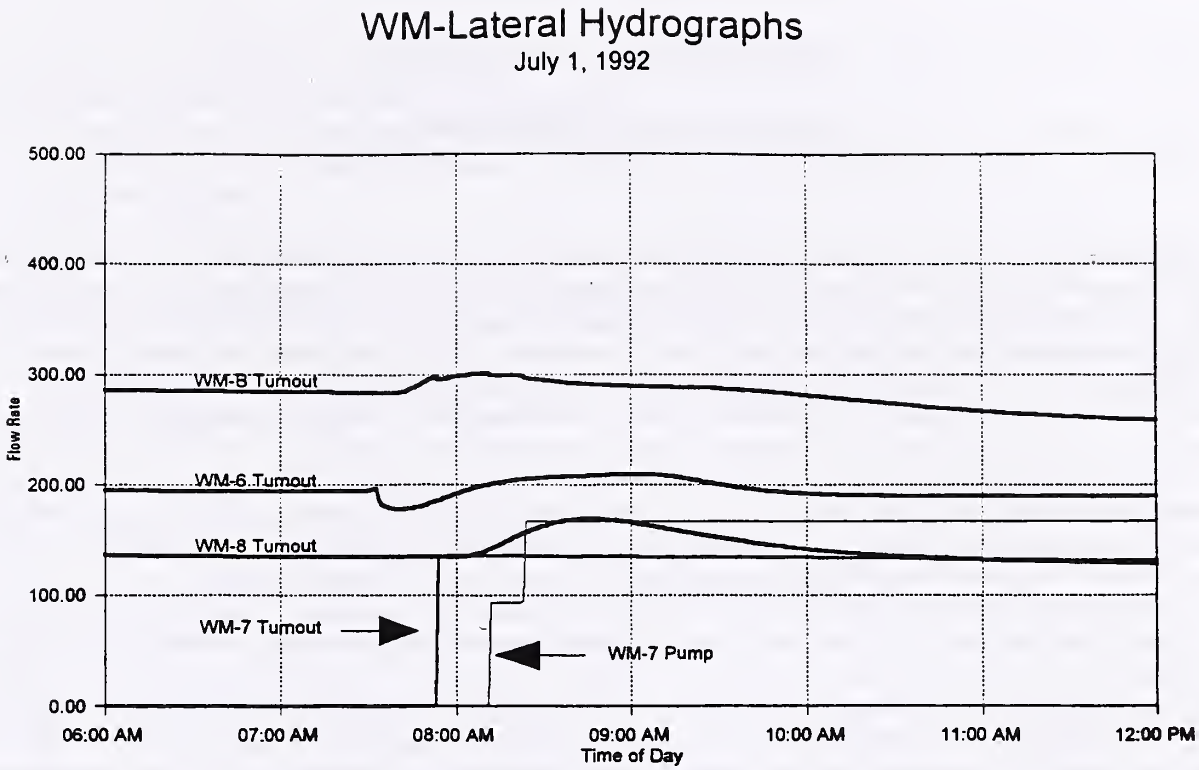


Figure 3. Canal WM: Calculated turnout flow rates (ℓ/s) for downstream part of canal.

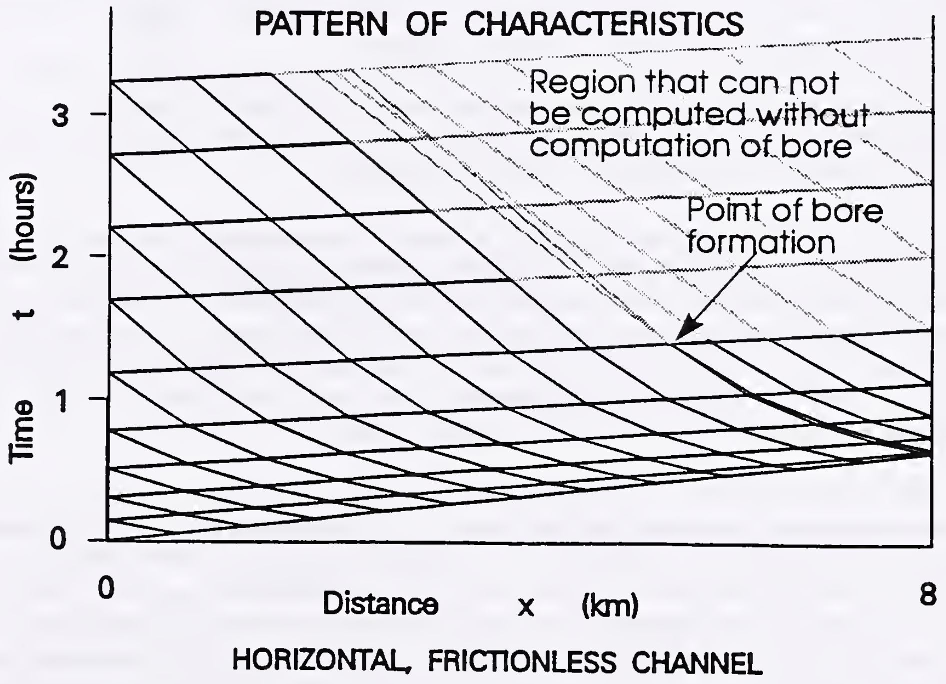


Figure 4. Time and distance grid showing bore formation in the reflected wave.

SURFACE IRRIGATION MODELING

T.S. Strelkoff, Research Hydraulic Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Throughout the irrigated world, water is applied to fields unevenly, and locally in excessive amounts, leading to wastage and to pollution of ground and surface waters receiving the excess. The interaction of the many variables significantly influencing the movement of irrigation streams down fields, and ultimately, the distribution of infiltrated water and the amount of runoff from the irrigation, is too complicated for simple calculation. A mathematical model--a numerical, computer solution of the pertinent governing equations--supplied with the conditions of the irrigation can, on the other hand, allow rapid determination of the consequences of a given physical design and management procedure. Systematic, repeated simulations allow determination of design parameters to yield optimum uniformity of infiltrated water and minimum runoff from the end of the field, as reported under a separate research project. This, in turn, can reduce the degradation of ground water supplies by excess irrigation water contaminated by fertilizers and pesticides, percolating below the root zone of the crop. Similarly, reduction and re-use of field runoff protects surface-water supplies downstream from irrigated fields.

Current models of surface irrigation require further development to extend the range of conditions they are designed to simulate and to increase the reliability of their mathematical procedures. New irrigation techniques generally precede attempts at simulation, so models must be revised to allow theoretical testing of the innovations. Furthermore, present models do not always complete a simulation. A physical condition that can arise with cut-back flows is a temporary retreat of the leading front of the stream, eventually halted and once again moving forward. The present model cannot simulate this motion. In addition, certain flow conditions, notably very slow advance on the order of a foot per minute, with potential incipient front-end recession, present poorly posed problems, both physically and mathematically. A potential computer response is the generation of a negative depth, which stops the calculation if inflow, however small, at the head end of the field has not yet been cut off.

The present treatment of surges overtaking previous releases is not realistic and needs improvement. Likewise, overflow into a drainage ditch through critical depth, as currently postulated, is not a realistic representation of current farm management--typically, the drainage ditch is given a sufficient depth of water to prevent the erosion that would occur if critical conditions were in fact present at furrow end.

All of these physical circumstances are likely to occur in the investigation of practices leading to efficient irrigation; the inability to simulate these properly hampers the search for an optimum design.

The current ARS surface-irrigation model, furthermore, in spite of improvements in format, still requires data entry more complicated than many potential users are willing to negotiate.

APPROACH: Restructuring of current programming and additional programming are underway to simplify code and extend the scope of application of the model. The equations governing the flow of water in the surface stream are known, and computer algorithms for solving these are generally straightforward. An exception is the case of non-monotonic stream advance, since a reasonable assumption regarding the effect of rewetting upon infiltration will have to be implemented. The current approach follows Smerdon and Blair, utilizing pieces of the infiltration-time curve corresponding to wetted periods. The current approach to very slow flow is simply to allow it to advance and retreat as the numerical approximations to the flow equations dictate.

FINDINGS: Distribution of the last formal version of the surface-irrigation simulation program, SRFR--Version 20, has slowed in the present year to just a few interested parties. An experimental version 20.4 has been released to a number of cooperating researchers, including several SCS offices. This newest version utilizes data files which include sufficient text to identify each entered number, for simple modification in any text editor. It is also characterized by on-line screen graphics depicting the simulated movement of the stream down the border or furrow, as well as the ultimate results of the simulation. The graphical view of the ongoing simulation allows a quick assessment of the behavior of the computational algorithms as well as the efficacy of the current design and management parameters. The last graphic, of the ultimate results of those parameters, confirms the impression.

It, furthermore, can be output to computer files for subsequent printing on a laser printer, or exported to auxiliary software, like CorelDraw, for slide making or pen-plotting.

It was found that, for reasonable simulation of flows in furrows characterized by an SCS intake family, the SCS intake coefficients must be multiplied by the ratio of SCS nominal wetted perimeter to the actual wetted perimeter calculated in the simulation.

The model is capable of simulating flows with a wide range of measured intake characteristics. Figure 1 shows measured infiltration (SCS) into a problem soil in Dunklin County, Missouri, underlain by a shallow impermeable layer limiting infiltration to just 1 1/2 inches on a field-wide basis (the infiltration shown is averaged over the wetted perimeter pertinent to the test). For the simulation, the measured points were fitted with a composite function, with the cross-over point at 180 minutes Figure 2 shows a series of simulations at different inflow rates and cutoff times in an irrigation system laid out in this soil. Trials similar to these lead to optimal management, balancing field nonuniformity against runoff volumes.

INTERPRETATION: To make a significant impact on surface-irrigation design and practice, computer models of the process must be of broad scope, fast, and reliable, yielding simulations for every reasonable combination of circumstances, and with convenient, user-friendly data input and graphical display of the results of any given set of design and management parameters. This is the aim of current development.

The simulation model is capable of providing quick results for various test combinations of design and management parameters, thus allowing these to be optimized.

FUTURE PLANS: Current deficiencies in model behavior as outlined above will be addressed. Given the large size of the model and the memory limitations of most computers in the field, flexibility in distributing that memory to the greatest benefit of the user will also be addressed. The latest versions of compilers and linkers will be investigated.

COOPERATORS: Dr. D.D. Fangmeier, The University of Arizona; Dr. Joel Cahoon, University of Nebraska; Keith Admire, SCS, Dexter, Missouri.

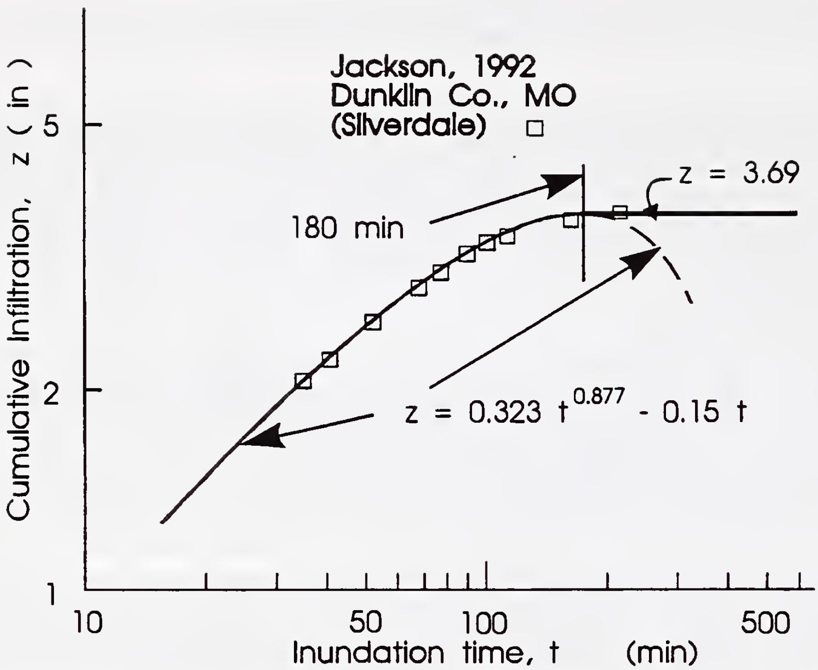


Figure 1. Cumulative infiltration into a problem soil, underlain by hardpan.

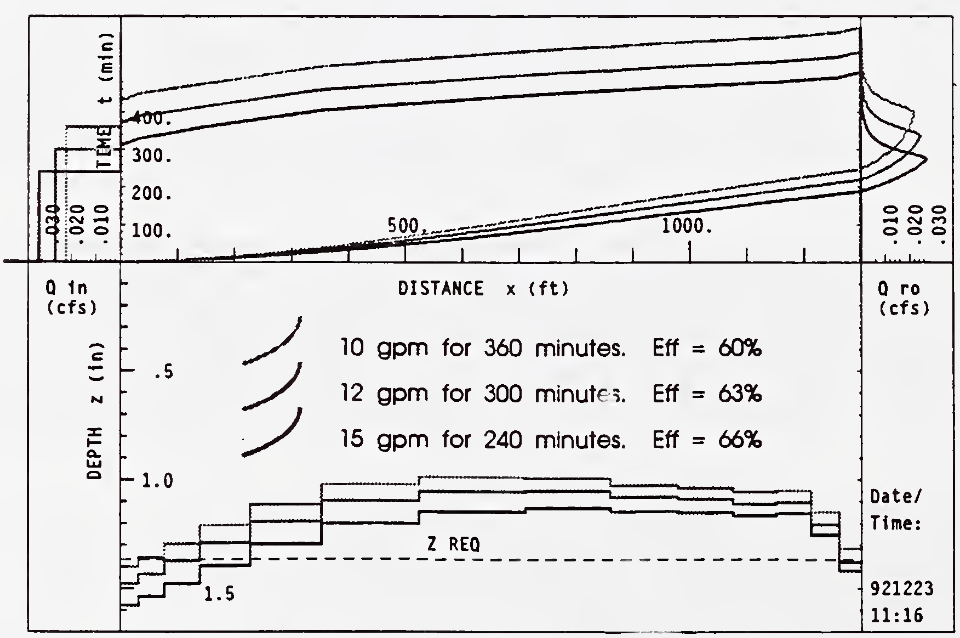


Figure 2. Simulations for optimizing irrigation management in the given soil.

SURFACE IRRIGATION SYSTEM DESIGN AND EVALUATION

A.J. Clemmens, Supervisory Research Hydraulic Engineer;
T.S. Strelkoff, Research Hydraulic Engineer; and
A.R. Dedrick, Supervisory Agricultural Engineer

PROBLEM: Mathematical models of water flow in surface irrigation have been developed over the last two decades. These are predictive models; that is, once the actual conditions are provided the model determines the results of the irrigation. In many cases, the infiltration and roughness conditions are not known and must be evaluated. While a number of evaluation techniques are available, different techniques are appropriate for different situations. Even when field properties for one irrigation are determined, they may be quite different for other irrigations under different crop and tillage conditions. Further, design should consider performance over the full range of expected conditions. If the design is functional over the full range of conditions, the irrigator need make only minor adjustments from irrigation to irrigation. More detailed feedback control has been studied under a separate research project (see 1990 USWCL Annual Research Report).

The objective of this project is to develop user friendly software for the evaluation, design, and operation of surface irrigation systems that is usable in differing irrigation settings.

APPROACH: Reliable predictive models are the first step in the development of surface irrigation software. Model development is discussed under a separate research project. There are two approaches to developing design results; refer to results already generated from a simulation model or search for an acceptable (or optimal) design solution by iterating with the simulation model. With current computing capability, the former is still preferred; however, as increasingly faster machines become available, the latter provides more latitude in design objectives and field conditions.

Generalized design and management guidelines must yet be developed from the models. These guidelines can be in the form of tabulated results, regression equations, or procedures for systematically applying the predictive models. This step is necessary for practical application of these predictive models. Several approaches will be taken in the development of these design guidelines. They include the development of 1) nondimensional solutions for general problems (e.g., optimal design) that can be computer coded, 2) design procedures that take into account the changes in field parameters that occur over the season, 3) sensitivity analysis of design input, and 4) interactive design or management aids that use search procedures to find solutions from predictive models.

Generalized solutions for level basin design have previously been generated with a simulation model. These results were based on SCS design criteria which specify that cut off of the irrigation stream is based on time from *a priori* knowledge of the distribution uniformity, (steady) flow rate and required application depth. Level basin operators rarely use time as the basis for changing irrigation sets because flow rates vary and attainable distribution uniformity is variable and unknown. Instead, they use a spot in the field to determine when to cut off the stream. Wattenburger and Clyma developed design solutions based on cutoff at the end of advance, which may be applicable for level basin design in developing countries where flow rates are highly unreliable. This suggests that the design approaches should be modified to consider advance distance at cutoff as a design criteria.

In addition, to provide a complete design package that describes "real world" conditions, the impact of soil spatial variability, surface irregularities, and non-uniform inflow streams on uniformity and efficiency need to be included. Various studies will be conducted to assess the impact of these conditions. Procedures will then be developed to account for these in the design and operating procedures. Needs also exist for a general program on field evaluation procedures to assist users in quantifying infiltration and roughness for actual field conditions to be used as input into these design and operational programs; and for efficient, robust search procedures for finding optimal designs reliably.

FINDINGS: The nondimensional design results for level basins were previously coded into a menu-driven design program. This program, BASIN, was intended to replace the SCS design charts. The entire set of nondimensional results were rerun with BRDRFLW, so that additional information could be provided on advance distance at cutoff,

advance time, and water depth. New procedures were developed to include design based on advance distance at cutoff. These new routines are still being tested.

INTERPRETATION: While significant advancements have been made on the development of predictive models, significant impact on surface irrigation performance will occur when these models can be incorporated into some form of user-friendly software. This must be done in the context of grower management practices.

FUTURE PLANS: A proposal has been developed with the International Institute for Land Reclamation and Improvement (ILRI) to 1) expand the BASIN program to include field evaluation procedures, 2) include design based on advance distance at cutoff, and 3) include statistical procedures to account for spatial variability and surface leveling precision. A book on level basins will be written to accompany the new program, BASIN2. This project will be initiated after the initial release of BASIN. Other cooperative efforts include a new project with The University of Arizona to develop design solutions for low-gradient, blocked end borders, a logical extension of the solutions for level basis; and review of current SCS design procedures for sloping furrows in the light of results from computer simulation of furrow flow.

Long-range plans are to develop a general software package for surface irrigation systems along the lines of BASIN2 but expanded to include sloping borders and furrows and to include the actual simulation model, as well as generated design results and evaluations. The University of Michigan has developed search procedures for surface irrigation parameter estimation. We will examine these procedures to determine their suitability for use in design.

COOPERATORS: N.D. Katopodes, University of Michigan; D.D. Fangmeier, The University of Arizona; T.A. McMahon, University of Melbourne, Australia; M. Jurriens, International Institute for Land Reclamation and Improvement, The Netherlands; W. Clyma, Colorado State University.

GROUNDWATER QUALITY PROTECTION

WATER REUSE AND GROUNDWATER

H. Bouwer, Research Hydraulic Engineer

PROBLEM: To define the role of groundwater recharge and recovery in the treatment and storage of sewage effluent for irrigation and other reuse.

APPROACH: Main approaches consist of technology transfer, using results of previous USWCL research and current research by others, and serving on committees and advisory boards for research projects, pilot-demonstration projects, planned projects, and issues in groundwater recharge with low quality water. Proposals were developed and tested for field investigations to determine feasibility of groundwater recharge under difficult soil and hydrogeologic conditions.

FINDINGS: Use of groundwater recharge and recovery in water reuse schemes is cost effective, increases system reliability, and improves aesthetics and public acceptance of water reuse, especially for potable purposes. Field investigations for a proposed project with difficult soil and vadose zone conditions include in-situ hydraulic conductivity measurements in the vadose zone to a depth of about 15 m to detect restricting layers, a one-acre infiltration test pond with 10 m-deep piezometers to detect perching groundwater above a potentially, restricting layer, and a well in the underlying aquifer to measure groundwater mound formation. The observed mound agreed with calculated mounds, indicating hydraulic continuity between the infiltration basin and the aquifer. Perching groundwater was not observed. Thus, the site is suitable for groundwater recharge by infiltration, but at rates that may be 5 - 10 cm per day, as compared to the 30 - 150 cm per day obtainable for "good" sites.

INTERPRETATION: Water reuse, as with other forms of recycling, is the ultimate form of resources management and conservation. Groundwater recharge and recovery offer a number of advantages in water reuse, but requires favorable hydrogeological conditions. The proposal of field investigations developed for less favorable conditions enables detection of fatal flaws that would preclude groundwater recharge as part of the reuse scheme.

FUTURE PLANS: The technology transfer work will continue and will include work on several major recharge and reuse schemes presently on the drawing board. Research may be initiated in connection with a large scale (200 mgd, 1000-2000 acres) proposed project. Most of this research would be done by a local university, but USWCL could play an active role in some aspects, like the clogging layer.

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

NITROGEN FERTILIZER AND WATER TRANSPORT UNDER 100% IRRIGATION EFFICIENCY

R.C. Rice, Agricultural Engineer; F.J. Adamsen, Soil Scientist;
D.J. Hunsaker, Agricultural Engineer;
H. Bouwer, Research Hydraulic Engineer; and
F.S. Nakayama, Research Chemist

PROBLEM: More than 75% of the water consumed in the arid southwest is used for irrigation. Agricultural chemicals used in irrigated crop production have been perceived as a threat to the quality of our groundwater supply. State health and environmental quality officials are increasingly formulating rules and regulations for agricultural chemicals. The trend in rising nitrate levels of groundwater suggests that nitrogen fertilizers are being transported beyond the root zone, apparently as a result of irrigation. Theoretically, irrigating at 100% irrigation efficiency will lead to zero deep percolation. Crop leaching requirements could be met when crops are not being grown, and when most of the applied nutrients have been used by the crop. However, no experimental evidence is available demonstrating that 100% irrigation efficiency during the growing season will eliminate or minimize the transport of nitrogen to the vadose zone. The effects of spatial variations in infiltration characteristics and the preferential flow of water in the soil profile can be expected to cause local zones of water and chemical movement beyond the targeted root zone.

Current technology and state of knowledge of downward movement of agricultural chemicals to groundwater are inadequate because they do not consider spatial variability and preferential flow, and because the actual processes of physical, chemical, and biological attenuations are not adequately understood.

The objective of this study is to determine the movement of water and nitrogen fertilizer in the soil profile when irrigating at 100% irrigation efficiency and to develop associated Best Management Practices (BMPs) to protect the quality of underlying groundwater. Particular emphasis is on establishing irrigation and nitrogen fertilizer management practices in hot, arid climates, which are effective in reducing nitrogen leaching losses below the root zone, and the role of preferential flow on water and nitrogen transport.

APPROACH: Cotton was grown using level basin flood irrigation in 1991. Nitrogen fertilizer was applied with the irrigation water (chemigation). The experimental design was a completely randomized block with six fertilizer-water application treatments and three replications. Each experimental plot was 81 m^2. A different conservative tracer was applied with each fertilizer application. Nitrogen status of the crop was correlated with leaf chlorophyll content as determined with a chlorophyll meter. This is a relatively new technique that may allow determination of nitrogen stress in the crop and when and how much fertilizer to apply. Water movement in the soil profile was characterized with soil water content and tracer analysis. Evapotranspiration was estimated from energy balance techniques using meteorological data collected at the site.

Experimental treatments were: 1) irrigation and fertilizer applications scheduled according to current farm practices with 100% irrigation efficiency; and 2) with 80% irrigation efficiency; 3) irrigation applied fertilizer applications scheduled according to residual soil, petiole NO_3-N feedback, and leaf chlorophyll content with 100% irrigation efficiency, and 4) with 80% irrigation efficiency.

FINDINGS: One of the tracers had a toxic effect on the cotton. Two days after the m-triflurobenzoic acid tracer was applied with the water, curling of the leaves was noted. Plants in two plots that did not receive the tracer did not show this symptom. The effect was more noticeable on the new growth and was evident through most of the growing season, although it did subside in late August. However, few bolls were set and production was severely curtailed. Because of this reaction to the tracer, no cotton yield data were obtained. Dry matter data were obtained, but the effect of the toxic reaction was much greater than the effect of the different nitrogen and irrigation efficiency treatments. Soil samples were taken after the growing season to a depth of 3 m.

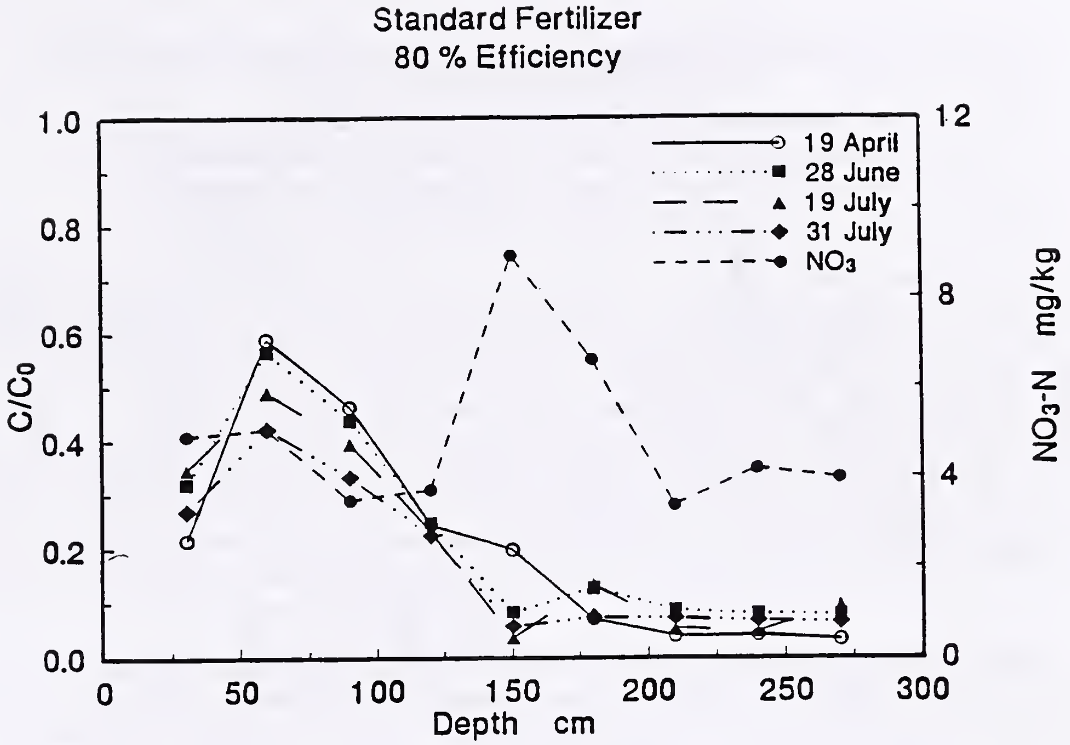
A total of 150 kg/ha N as urea-ammonium nitrate (UAN) was applied to the standard practice plots in two 75 kg/ha applications. The first was applied at planting and the second on June 28. Because of the toxic effect on the cotton, biofeedback data were inconclusive and could not be used for scheduling fertilizer application. A total of 125 kg/ha N was applied to the BMP plots in five 25 kg/ha applications. Analysis of the tracer and nitrate

concentrations in the soil profile are shown in Figures 1-4. Each point represents the average of 12 samples. The tracer concentrations are expressed relative to the applied concentration, where the nitrate is expressed in mg/kg of soil. There appears to be no difference between the standard practice and BMP on tracer and nitrate movement. However, at 100% irrigation efficiency for both the standard and BMP treatments, the tracer remained in the upper 100 cm of the soil profile. The maximum NO_3-N concentration was at 60 cm for the 100% efficiency plots, but was between 100 and 150 cm at 80% efficiency. There appears to be more NO_3-N in the profile at 100% efficiency, indicating deep percolation may have occurred at 80% efficiency. Because the nitrogen was not tagged, no distinction could be made between the applied and residual nitrogen.

INTERPRETATION: Preliminary analysis indicates that 100% efficiency irrigation during the growing season may retain higher NO_3-N levels in the upper portion of the soil profile resulting in fewer losses in nitrogen by deep percolation. Results of the different nitrogen application practices were not conclusive in this study.

FUTURE PLANS: The experiment will be repeated in 1993, using wheat and cotton. An additional treatment of 20% deficit irrigation will be included. The transformation and mineralization of nitrate during the fallow period will be monitored. There is some indication that mineralization of organic nitrogen from crop residue may be an important source of nitrate.

COOPERATORS: Dr. J.E. Watson, The University of Arizona, Maricopa Agricultural Center



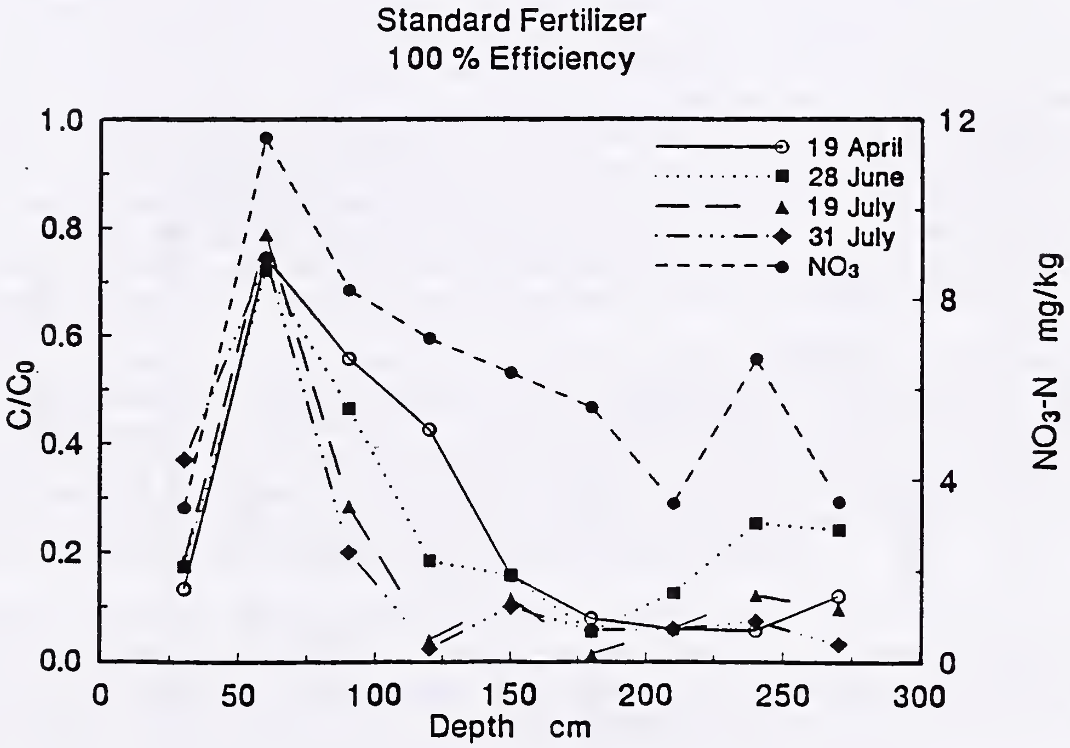


Figure 1. Nitrate and tracer concentrations for standard fertilizer application at 80% and 100% irrigation efficiency. The tracer concentrations are relative to the applied concentration. Application dates for the tracers are shown in the legend.

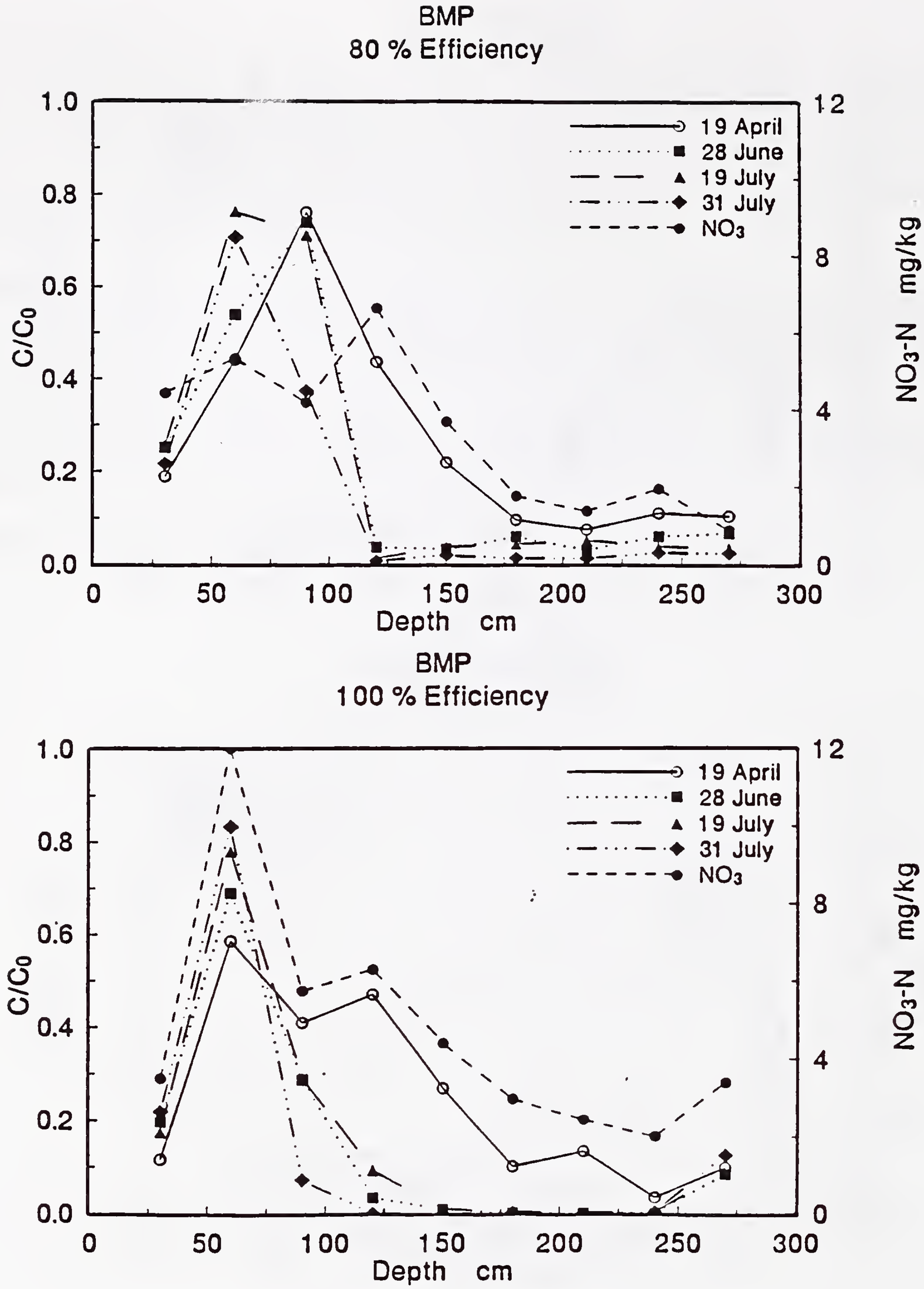


Figure 2. Nitrate and tracer concentrations for BMP fertilizer application at 80% and 100% irrigation efficiency. The tracer concentrations are relative to the applied concentration. Application dates for the tracers are shown in the legend.

NITROGEN BUDGETS OF IRRIGATED CROPS USING NITROGEN-15 UNDER HIGH EFFICIENCY IRRIGATION

F.J. Adamsen, Soil Scientist; R.C. Rice, Agricultural Engineer;
F.S. Nakayama, Research Chemist; D.J. Hunsaker, Agricultural Engineer; and
H. Bouwer, Research Hydraulic Engineer

PROBLEM: Nitrate is the pollutant most commonly found in groundwater. The contribution of nitrate to groundwater pollution carried by deep percolating irrigation water could be reduced or eliminated by the development of existing and new technologies. This requires a better understanding of the total nitrogen required by the crops produced and the timing of nitrogen uptake, as well as chemical and water transport in the soil environment. Careful timing of fertilizer applications and prudent operation of irrigation systems to reduce the amount of water lost below the rooting zone can reduce the movement of water and chemicals to groundwater. Theoretically, irrigating at 100% efficiency and carefully controlling fertilizer amounts and timing of applications should lead to no deep percolation and no fertilizer leaching losses. Crop leaching requirements could be met when soil nitrate levels were lowest. However, because of spatial variability, preferential flow, and incomplete uptake of nitrogen by the crop, 100% irrigation efficiency and optimum nitrogen management may still produce some deep percolation and transport of nitrate to groundwater.

APPROACH: Research is being conducted through a series of experiments to evaluate irrigation efficiency theory and nitrogen management practices. Wheat was grown in the 1991-1992 season using level-basin flood irrigation. Wheat was planted again in 1992-1993. Future experiments will use cotton as the crop and other irrigation methods, such as drip and sprinkler irrigation. The experimental design is a completely randomized block with six fertilizer-water application treatments and three replications. Experimental plots were approximately 81 m^2 in size in 1991-1992 and 108 m^2 in 1992-1993. A different conservative tracer was applied with each irrigation and nitrogen-15 tagged fertilizer was applied to three micro-plots in each main plot in 1991-1992 and two micro-plots in 1992-1993. Micro-plots are approximate 1.1 m^2. This allows a complete water and nitrogen balance, including the amount of nitrogen removed with the harvested crop, percolation losses, and volatile losses. The nitrogen status of the crop was determined by tissue analyses and leaf chlorophyll content with a chlorophyll meter. Chlorophyll measurements may allow a rapid cost effective method for determining the nitrogen status of a crop in real time and may be useful in determining the amount and timing of fertilizer nitrogen application. Water movement in the soil profile was characterized by soil water content and tracer analysis. Evapotranspiration (ET) was estimated from energy balance techniques.

Experimental treatments include 1) a "standard" irrigation and fertilizer management procedure where irrigation and fertilizer applications are scheduled according to current farm practice with 100% irrigation efficiency or 1.0 ET, 2) same as treatment 1 except with 80% irrigation efficiency or 1.2 ET, 3) same as treatment 1 except with a deficit irrigation equivalent to 120% irrigation efficiency or 0.8 ET, 4) irrigation water applied fertilizer application (chemigation) scheduled according to residual soil, petiole, NO_3-N feedback, and leaf chlorophyll content with 100% irrigation efficiency, 5) same as treatment 4 except with 80% irrigation efficiency, and 6) same as treatment 4 except with a deficit irrigation equivalent to 120% irrigation efficiency.

FINDINGS: In 1991-1992, the standard fertilizer treatment was 45 kg of N ha^{-1} applied broadcast at planting as $(NH_4)_2SO_4$ and an additional 90 kg of N ha^{-1} applied in the irrigation water 87 d after planting. The BMP nitrogen treatment was 22.5, 68 and 13 kg of N ha^{-1} applied 58, 87, and 108 d after planting, respectively. The winter and spring of the 1991-1992 growing season were unusually wet. The wet conditions delayed planting of the crop until January 5, 1992. Due to poor stand establishment, the crop was replanted in late January. The wet year also resulted in only small differences in applied irrigation water between the water treatments.

The grain and straw yields of the micro-plots were comparable to those of the main plots (Fig. 1). Grain yields were low as a result of late planting. Yields averaged less than 2500 kg ha^{-1} and the BMP 100% efficiency treatment was lower than other treatments. Two BMP 100% efficiency plots that were affected by previous application of bromocil that reduced the yield in these plots.

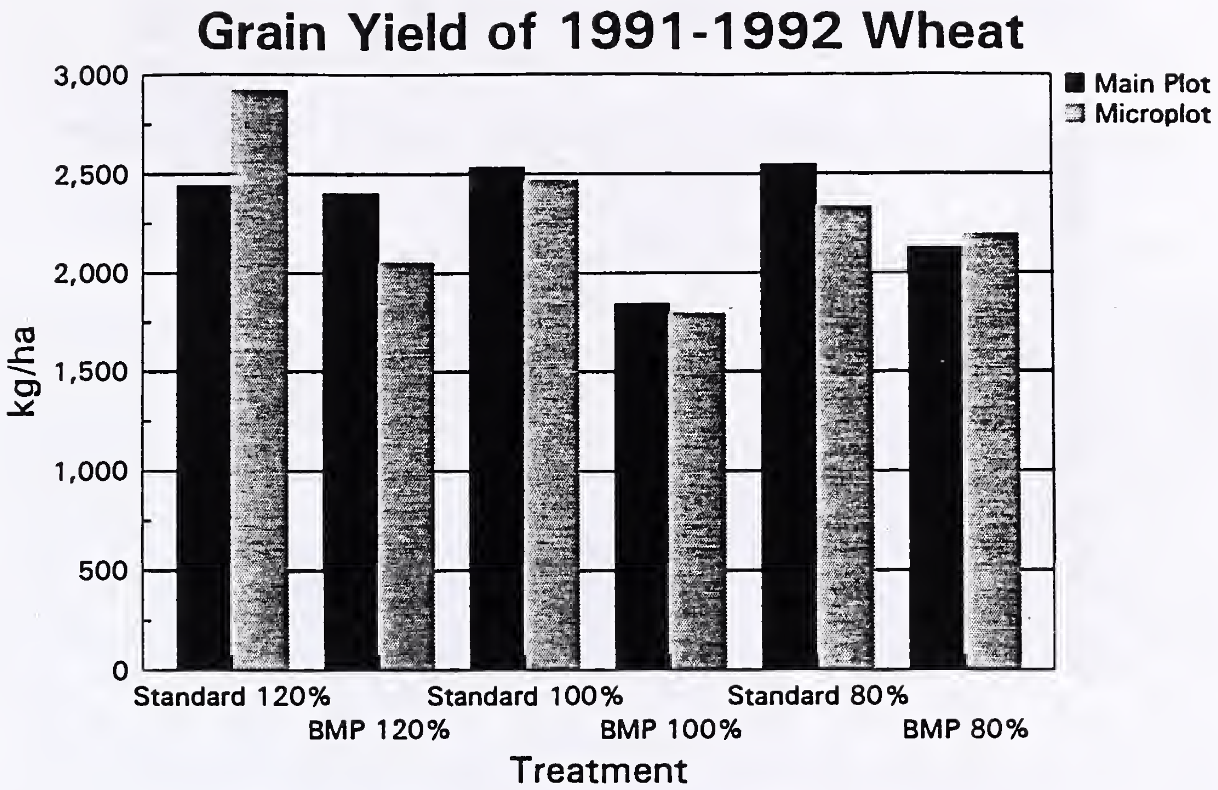
No differences in total N were found among treatments at any depth (Fig. 2). All of the standard N treatments showed a bulge of NO_3-N below 120 cm suggesting that the amount of fertilizer applied was in excess of plant needs. There is a slight trend in the data showing deeper movement of NO_3 with increasing water application. The increase in NO_3 at the 270-cm depth in the BMP 80% efficiency treatment indicates that excess water will move NO_3 below the root zone, even when fertilizer applications are reduced and timed to correspond to plant demand. When the nitrogen-15 analyses are completed, it will be possible to determine the source of the NO_3 in the subsoil.

INTERPRETATION: Preliminary results indicate that more of the applied fertilizer is confined to the root zone under 100% efficiency irrigation and improved fertilizer management during the growing season than with the standard treatments and lower irrigation efficiency. Improved water and fertilizer management reduce production costs for the producer and also decrease the amount of NO_3 moving into the groundwater.

FUTURE PLANS: In 1993, a study similar to the one on wheat will be initiated using cotton as the crop. Additional irrigation methods also need to be investigated. The rates of movement of chemical tracers and labelled nitrogen will be used to assess the impact of preferential flow. The data set should be suitable for evaluating current soil models which predict the quality of water moving below the root zone. If no suitable models exist, a model development and verification effort can be initiated.

COOPERATORS: Dr. J.E. Watson, The University of Arizona Maricopa Agricultural Center

QUASI-POINT SOURCES OF AGRICULTURAL GROUNDWATER CONTAMINATION



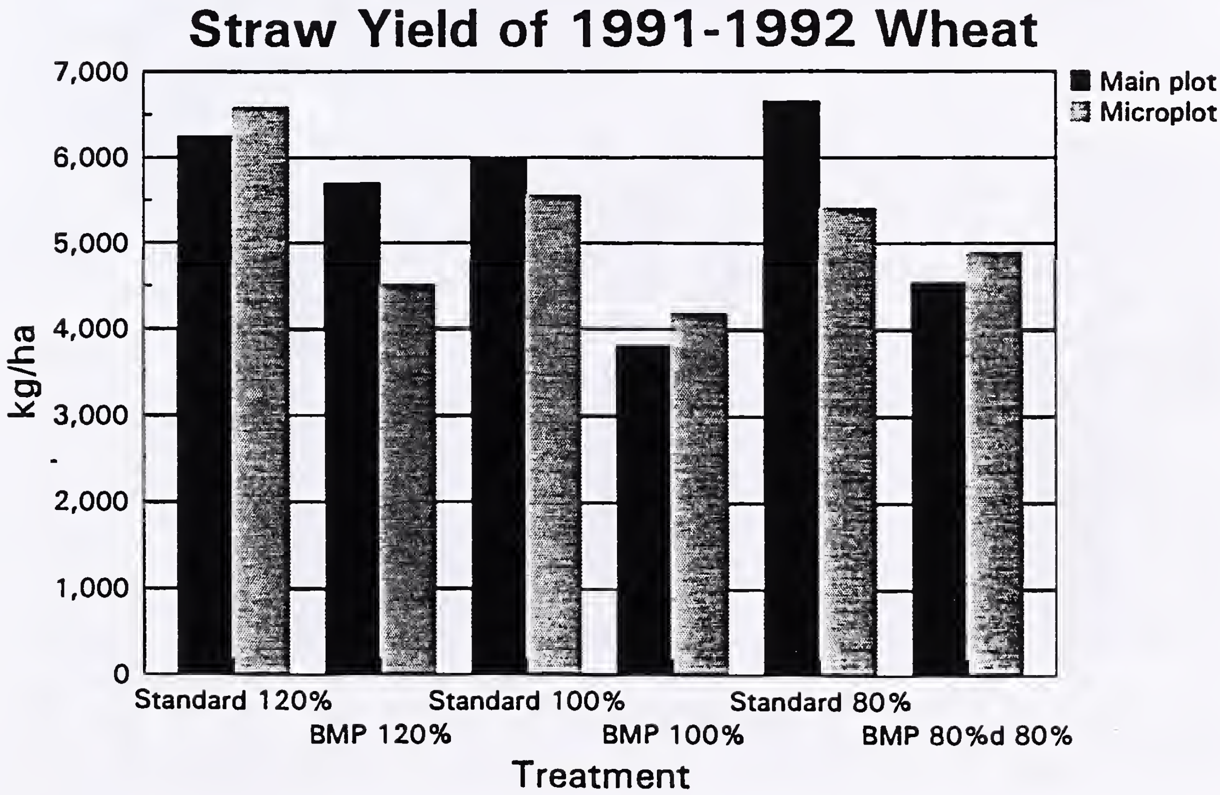
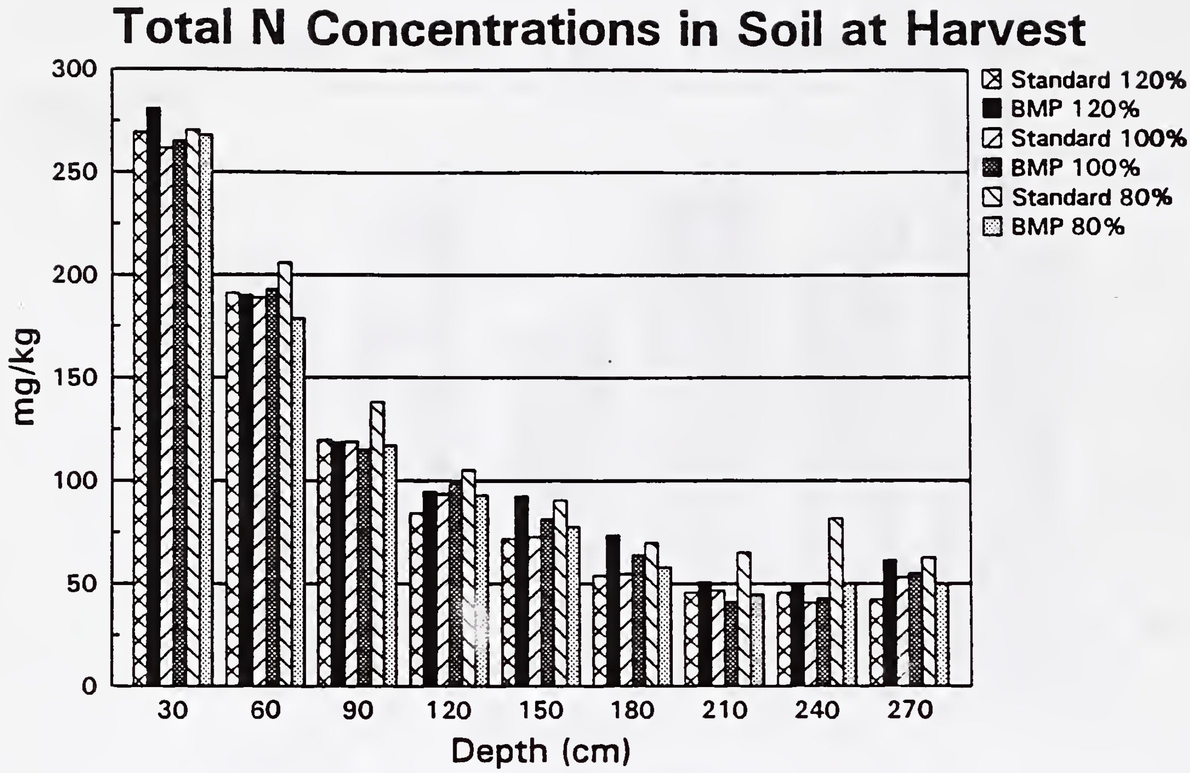


Figure 1. Wheat grain and straw yield from nitrogen and water management plots for the 1991-1992 growing season.



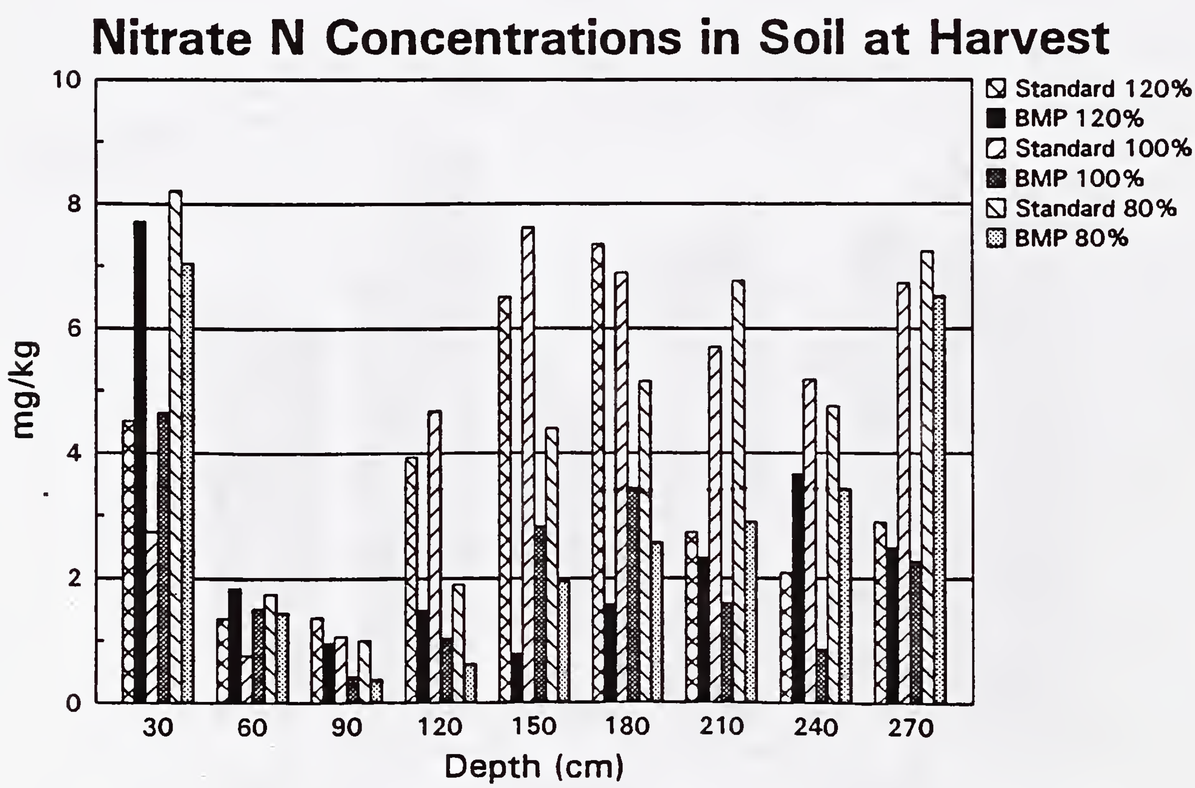


Figure 2. Total soil nitrogen and nitrate nitrogen concentrations in nitrogen and water management plots after wheat harvest in 1992.

SIMULATION OF CHEMICAL TRANSPORT WITH SURFACE IRRIGATION FLOWS

T.S. Strelkoff, Research Hydraulic Engineer;
F.J. Adamsen, Soil Scientist; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Irrigation management influences the quality of both surface and groundwater supplies. Chemigation introduces agricultural chemicals into the irrigation water. Initially clean irrigation water picks up agricultural chemicals and naturally occurring minerals, some toxic, from the surface of fields and from contact by percolation through the porous soil medium. Nitrogen, chlorinated organic compounds, and heavy metals, for example, brought to farm fields in the course of agricultural operations, and naturally occurring materials such as, selenium, can be transported to surface or subsurface water supplies by the movement of irrigation water, to the detriment both of human consumers of the water resource and wildlife dependent on these bodies of water.

The transport, transformation, and ultimate fate of chemical components of the irrigation water depends on the quantities of water remaining in the root zone after the irrigation, the quantities running off the end of the fields into drainage ditches and canals, and the quantities that continue to percolate through the soil, eventually entering either a groundwater aquifer or a river fed from groundwater seepage. The chemical and physical reactions between the water, the soil medium, and the particular chemicals involved significantly influence the transformation and ultimate fate of the chemical constituents.

Preferential flow, fingering of the water front advancing downward through the soil medium, arises both as the result of nonhomogeneous soil, with worm and root channels, and layering of soils, with a layer of low permeability overlying one of great permeability. This results in more rapid transport of waterborne constituents to the groundwater table.

In the porous subsurface medium, many existing models view variation in only one dimension, the vertical, assuming no movement parallel to the stream flow. However, *interflow* is known to occur, especially on steep slopes, and in fact provides the principle means of transport of ground water, along with its chemical constituents, into surface streams.

The goal of this research effort is a predictive tool, a computer model, capable of simulating the response of a given agricultural field and its geologic site to one or another irrigation-management practice. Computer simulations would allow swift comparisons amongst various trial management modes in a program to seek optimum solutions. This would make possible recommendations on the basis of environmental considerations as well as upon water conservation and crop yield.

APPROACH: Two different problems comprise the subject of investigation: (1) transport of a contaminant by irrigation water from a contaminated soil-surface layer to stream flow and to the ground water via deep percolation, and (2) the longitudinal distribution of a chemical introduced nonuniformly in the irrigation-inflow hydrograph, e.g., a pulse of chemical introduced at some time after the start of water inflow at a constant rate.

Both problems are to be treated by a plane two-dimensional mathematical simulation, coupling a solution of the Navier-Stokes equations augmented with a two-equation turbulence model in the surface stream to a solution of the equations for unsaturated flow in a porous medium in the underlying soil. The two regions share a common vertical velocity field at the interface. The free surface of the deforming finite-element grid used in the simulation is found from the kinematic boundary condition on the equations of motion. The shear calculated at the channel bed is used to determine incipient sediment motion. The air-water-soil singularity at the wave front is replaced by a finite segment of arbitrarily short length treated as a zero-traction outflow boundary.

Mass transport is modeled in the entire system through dispersivities calculated from the flow equations. Sorption and desorption are incorporated in terms of both equilibrium and nonequilibrium kinetics of semi-empirical determination. The same is true for volatilization, degradation and leaching processes, incorporated as sink terms in the mass transport model.

A physical model with a graded sand bed is contemplated for verification of the mathematical model. Preliminary dimensions have been established.

FINDINGS: A mathematical model based on the given approach has been constructed. Special attention has been paid to the interface between surface and subsurface flows. Slip and no-slip conditions have both been programmed, because there is no *a priori* indication which assumption is better justified. The interface layer is independently modeled by laminar flow through a semi-infinite staggered array of cylinders, allowing detailed calculation of flow and particle tracks. A particle-tracking technique has been developed to determine pathlines of contaminants inserted into the system at arbitrary locations.

INTERPRETATION: The model is too new to have yielded significant results to date. It shows promise, however, in being capable of simulating the subject phenomena to a useful degree. With increased reliability and verification, it should serve both as a research tool in evaluating one or another irrigation management, and as a theoretical base for more approximate, more practical simulations.

FUTURE PLANS: The mathematical model will be exercised over a range of practical conditions to establish and strengthen its reliability. Specific chemical constituents to be incorporated into the model will be selected, along with currently available figures on reaction kinetics, to substitute for the present hypothetical assumptions. The physical flume will be built and operated to test the various model assumptions, establish appropriate values for numerical solution parameters, and verify its performance.

COOPERATORS: N.D. Katopodes, University of Michigan.

QUASI-POINT SOURCE ASSESSMENT: PESTICIDES AND NITRATES

H. Bouwer, Chief Engineer; and
A.J. Clemmens, Supervisory Research Hydraulic Engineer

PROBLEM: Degradation of groundwater quality has been associated with extensive use of agricultural chemicals in many places throughout the United States. A study carried out by the EPA (EPA Rpt 1990) showed that nitrate levels in 1.2% of community wells and 2.4% of rural domestic wells exceed the EPA's drinking water standard of 45 mg/ℓ. Similarly, the study found that 10.4% of community wells and 4.2% of rural domestic wells have detectable levels of pesticides. Defining the sources of such chemicals in drinking water wells is essential for starting an effective water quality program. Sources of nitrate and pesticides may include local applications (point or farmstead source) and areal applications on fields (non-point or field source) near a production well. The main objectives of this study are: 1) to develop a method to determine whether the agricultural chemicals (pesticides and nitrates) observed in a well are from a point or non-point source; 2) develop suitable remedial action; and 3) recommend best management practices to prevent groundwater contamination by agricultural chemicals.

APPROACH: Two approaches have been implemented to distinguish between point and non-point sources, a numerical/analytical modeling technique and chemical isotope analysis. Each approach will provide an independent means to distinguish between sources. The results of the chemical isotope analysis will be used to verify the corresponding numerical simulation results. In the first approach, two numerical models were selected to simulate the transport and transformation of contaminants under unsaturated/saturated conditions. For different hydrologic conditions and plume sizes, sets of disappearance type curves for water from continuously pumped wells have been generated. In the future, the concentration versus time curve for an actual production well will be compared with the type curves to identify the source and the extent of pollution. Due to the wide ranges of hydrologic and boundary conditions, an infinite number of disappearance curves can be generated. The challenge is to condense them into a relatively small number of dimensionless type curves. For relatively simple hydrologic settings, the analytical model gives a closed form for the relationship between the aquifer parameters, plume size, and predicted concentration (Eq. 1). This may limit the number of type curves and lead to a more practical situation.

The analytical model is valid for homogeneous, isotropic porous medium having uniform flow with a seepage velocity v. The medium is assumed to be free of the solute species of concern, and at a certain time a strip source with length a is introduced along the y-axis (Fig. 1). The concentration of the solute is assumed to diminish exponentially with time (Eq. 2).

Varying the length of the contaminant source can simulate point and non-point sources. Linking this model with the observed concentration hydrograph then gives an estimate for the extent of the contamination source. The second approach utilizes the ability of boron isotope ratios to trace contaminants. Chemicals, such as nitrate and pesticides, are often difficult to trace because of chemical instability. Nitrogen can be oxidized or reduced in the soil and during transport through the vadose zone. Pesticides and other hydrophobic micropollutants are often biodegraded into secondary byproducts, and, in addition, absorb onto organic rich substrates. Recent work by Davidson (1989) to determine contaminant origin and to monitor transport based on isotope ratios has shown promise, because it focused on the more conservative co-migrating species that still give a signature of the source of the contaminant. One such species is boron; the signature is derived from the determinants of the stable isotopic ratio B.

The element boron is essentially present in water and the isotopic composition of boron can be used as an intrinsic tracer for various sources of groundwater contamination. To use B as a tracer, each contaminant source must have a unique isotopic ratio. The determinants of the ratio B include such chemical processes as evaporation, sorption onto surfaces, and processing by living organisms. Nitrate and the accompanying boron are carried in the waters of many contaminant sources; sewage effluent, chemical fertilizer, and manure all contain nitrate. Each of these sources has a unique origin and should exhibit unique boron isotope ratios. Many of the other chemical species in these sources may exhibit unique isotopic ratios, but boron has been selected as a tracer, because it is relatively conservative in the soil and is readily extracted and analyzed. Point and non-point application of a given chemical species may occur in the ways outlined in the following two cases. Tracing contaminant sources using B is effective only in the second case, where a single contaminant from two origins is applied in local and areal fashions.

Case 1: A single contaminant source introduced to the ground within a localized area (point source) may also be spread over a large area and serve as a non-point source. For example, on a farm, fertilizer stored in a leaky tank will provide a point source of nitrate contamination; the same fertilizer spread on a field will constitute a non-point source. Since the primary contaminant and the accompanying boron in each application are identical, the isotopic ratios are the same when the contaminant enters the soil. Chemically conservative boron fractionates little in the soil; therefore, the isotopic ratios of the point and non-point sources remain identical along the flow path and in the ground water, thus eliminating the usefulness of boron as a tracer. Boron is also ineffective for tracing pesticides, since a single pesticide is likely to be applied both locally (leaky storage tank) and aerially. A method does, however, theoretically exist for approaching the problem of point and non-point contamination with a pesticide. Due to the chemical instability that pesticides exhibit during transport to the groundwater, pesticides should degrade differently along different flow paths. It may be possible to distinguish different flow paths by detecting distinct degradation products. This would, however, be an extremely difficult method to apply in field situations, since degradation rate is a function of the microbiota, redox environment and soil properties at an individual site.

Case 2: Where multiple sources of a single contaminant exist, local and areal contamination from different sources may result. For example, on a farm, a household septic system provides a point source of nitrate contamination, while the field application of fertilizers serves as an areal source. In this case, the point source and the non-point source both possess a unique isotopic ratio before the application of the chemicals. With a conservative species like boron, little fractionation is expected along the flow path; therefore the ratios found in groundwater represent those found in the contaminant sources. The analysis relies on obtaining samples of the sources involved to determine the characteristic boron isotope ratio of each source. The boron concentration and B of the background groundwater must also be, obtained because it, too, represents a source of boron. If these requirements are satisfied, one could actually distinguish the water-carrying septic system nitrate from water carrying nitrate derived from fertilizer.

FINDINGS AND INTERPRETATION: The numerical modeling technique was used to generate disappearance type curves for different plume sizes. A nitrate was modeled as a conservative contaminant, then a decay constant was added to represent the reactive contaminant, i.e., pesticides (k = 0.2 cm gm, decay constant = 0.0035 d). The variable hydrologic parameters were the hydraulic gradient, the aquifer transmissivity, and the dispersion coefficient. Analysis of the generated concentration hydrographs showed that, for a small plume size, i.e., local area, the concentration in water from a pumped well decreases sharply with time. For a spatially distributed area, the contaminant disappears gradually with a different slope for the straight part of the curve. This may give a rough estimate of the extent of the plume. These curves can be used to get an estimate of the plume size using the following procedure: 1-plot the relative concentration versus time of the contaminant in a pumping well; 2-determine the aquifer's hydrologic parameters; 3-choose the suitable type curve by matching the hydraulic conditions; and 4-match the observed hydrograph with the type curves to determine a rough estimate of the plume extent.

FUTURE PLANS: For a more practical application of the method, the analytical solution mentioned above will be connected to an expert system/neural network that can predict the extent of the plume represented by a given concentration hydrograph. Developing this system will eliminate the need for generating and matching large numbers of the disappearance type curves. As a complementary method for distinguishing contaminant sources, field data will also be collected for chemical isotope analysis. The results from both techniques will be combined to develop the suitable remediation policy.

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EPA Rpt. 1990. Nat. Surv. of Pest. in Drinking Water Wells, Ph. I Rpt. EPA 570/9-90-015, PB91-125765. 98pp.

COOPERATORS: T. Maddock III, Professor; L.G. Wilson, Hydrologist; R.L. Bassett, Associate Professor; N.G. Shafike and J. Leenhouts, Research Assistants, The University of Arizona

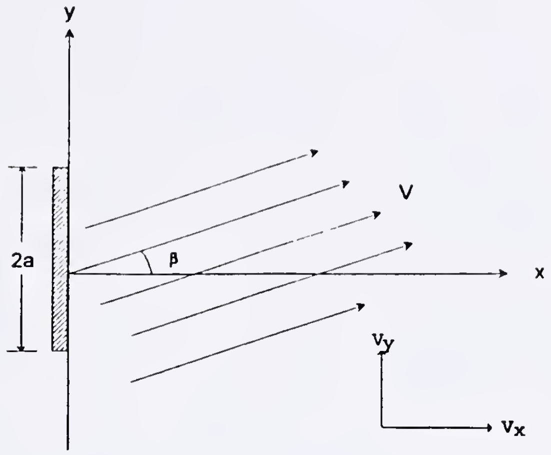

Figure 1. Schematic diagram showing the two-dimensional plan. Dispersion model with uniform flow making an angle β with χ-axis.

Table 1. The analytical solution to the two-dimensional plane dispersion model (Cleary and Unge, 1978) may be presented as:

$$C(x,y,t) = \frac{C_o x}{4(\pi D_x)^{1/2}} \exp\left(\frac{v_x x}{2D_x} - \alpha t\right) \cdot \int_0^{t/R} \exp\left\{-\left(\lambda R - \alpha R + \frac{v^2 x}{4D_x}\right)\tau - \frac{x^2}{4D_x \tau}\right\} \tau^{-3/2}$$

$$\cdot \left\{ erf\left\{\frac{a - y}{2(D_y \tau)^{1/2}} + \frac{v_y}{2}\left(\frac{\tau}{D_y}\right)^{1/2}\right\} + erf\left\{\frac{a + y}{2(D_y \tau)^{1/2}} - \frac{v_y}{2}\left(\frac{\tau}{D_y}\right)^{1/2}\right\}\right\} d\tau \quad (1)$$

The initial and boundary condition of this mathematical model may be written as:

$$c(0,y,t) = c_o e^{-\alpha t} \qquad -a \le y \le a$$

$$C(0,y,t) = 0 \qquad \textit{for other values of } y$$

$$\lim_{y \to \pm\infty} \frac{\partial C}{\partial y} = 0 \quad \textit{and} \quad \lim_{x \to \pm\infty} \frac{\partial C}{\partial x} = 0 \quad (2)$$

PREDICTING EFFECTS OF INCREASING ATMOSPHERIC CO_2 AND CLIMATE CHANGE ON YIELD AND WATER USE OF CROPS

EFFECTS OF FREE-AIR CO_2 ENRICHMENT (FACE) ON THE ENERGY BALANCE AND EVAPOTRANSPIRATION OF COTTON

B. A. Kimball, Supervisory Soil Scientist;
D. J. Hunsaker, Agricultural Engineer; and
W. A. Dugas, Micrometeorologist, Texas A&M University

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. Such increases in CO_2 and possible climate change could affect the hydrologic cycle and future water resources. One component of the hydrologic cycle that could be affected is evapotranspiration (*ET*) which could be altered because of the direct effects of CO_2 on stomatal conductance and on plant growth. The object of this experiment was to evaluate the effects of elevated CO_2 on the ET of cotton.

APPROACH: The evapotranspiration measurements were one component of the much larger Free-Air CO_2 Enrichment (FACE) project which sought to determine the effects of elevated CO_2 on plant growth, yield, and many physiological processes, as well as water use. Four toroidal plenum rings of 25 m diameter constructed from 12" irrigation pipe were placed in a cotton field at Maricopa, Arizona, shortly after planting. The rings had 2.5 m high vertical pipes with individual valves spaced every 2 m around the periphery. Air enriched with CO_2 was blown into the rings and exited through holes at various elevations in the vertical pipes. Wind direction, wind speed, and CO_2 concentration were measured at the center of each ring. A computer control system used wind direction information to turn on only those vertical pipes upwind of the plots, so that the CO_2-enriched air flowed across the plots, no matter which way the wind blew. The system used the wind-speed and CO_2-concentration information to adjust the CO_2 flow rates to attain a near-constant 550 ppm by volume CO_2 concentration at the centers of the rings. Four matching CONTROL rings at ambient CO_2, but with no air flow, were also installed in the field.

The determination of the effects of elevated CO_2 on ***ET*** by traditional chambers is fraught with uncertainty, because the chamber walls that restrain the CO_2 also affect the wind flow and the exchange of water vapor. Therefore, an energy balance approach was adopted, whereby ***ET*** was calculated as the difference between net radiation, R_n, soil surface heat flux, G_0, and sensible heat flux, H: $\lambda ET = R_n - G_0 - H$. R_n was measured with net radiometers and with soil heat flux plates. ***H*** was determined by measuring the temperature difference between the crop surface and the air and dividing the temperature difference by an aerodynamic resistance calculated from a measurement of wind speed. The air temperature was measured with an aspirated psychrometer, and the crop surface temperature was measured with infrared thermometers mounted above each plot.

FINDINGS: Two days were selected for presentation of diurnal energy balance patterns--July 11 [Day of Year (DOY) 192] and August 8, 1991 (DOY 220). Both days were cloud free, except just after sundown on DOY 220, when a wind storm arrived. At that time the hourly average wind speeds increased from less than 1 m/s to about 4.5 m/s, which is not especially severe, but the data from this time did serve to illustrate the sensitivity of the energy balance technique to unusually high winds. DOY 192 was unique, in that a 67% eclipse of the sun occurred at 11:42. This provided a strong, gradually-changing, 2-hour-long perturbation of usual cosine bell solar radiation pattern, unlike the uneven perturbations due to the random passage of clouds. Therefore, this day provided an additional illustration of the ability of the residual energy balance technique, as well as the other methods, to determine ***ET*** with a radiation regime.

The diurnal partitioning of energy among R_n, G_0, H, and λET was very similar for both the CONTROL and FACE plots on both DOY 192 and 220 (Fig. 1). G_0 and H generally tended to be of about the same magnitude and of opposite sign. Consequently, λET tended to follow R_n fairly closely. In the mornings on both DOY 192 and 220 and for both CONTROL and FACE, λET was almost identical to R_n. In the afternoons, λET tended to be somewhat larger. When the wind storm arrived at hour 20 on DOY 220, H was abruptly larger (more negative), and consequently, λET was calculated to be larger also as R_n became close to zero.

Figure 2 shows daily ***ET*** values from the energy balance, as well as those determined from complementary measurements of soil water balance and of stem flow. There is good agreement among these three very different methods of measurement, although the energy balance values were slightly higher than the others, and the energy balance data suggest the FACE ***ET*** was slightly more than the CONTROL ***ET***. However, an error analysis of the energy balance data revealed that the difference was within the magnitude of error in net radiation measurement.

INTERPRETATION: Elevated CO_2 concentration appears to have little effect on evapotranspiration rate. Apparently, any decreases in stomatal conductance are being compensated by counter increases in leaf temperature and leaf area.

FUTURE PLANS: Current plans are to conduct a FACE Wheat experiment from about December 1, 1992 through May 1993. ***ET*** will again be determined from energy balance measurements.

COOPERATORS:

Brookhaven National Laboratory
G. Hendrey, K. Lewin, J. Nagy
Grassland Protection Research (USDA-ARS, Temple, Tx)
H. Johnson
Manhattan College
L. Evans
National Soil Dynamics Laboratory
H. Rogers
Russell Research Center (USDA-ARS)
D. Akin
University of Arizona
R. Rauschkolb, S. Leavitt, D. Fangmeier
University of Florida (USDA-ARS)
L. Allen
U. S. Water Conservation Laboratory
P. Pinter, F. Nakayama, G. Wall, R. Garcia, S. Idso
Western Cotton Research Laboratory
J. Mauney, D. Hendrix, D. Akey, J. Radin, N. Bhattacharya

with support from the Department of Energy, as well as ARS.

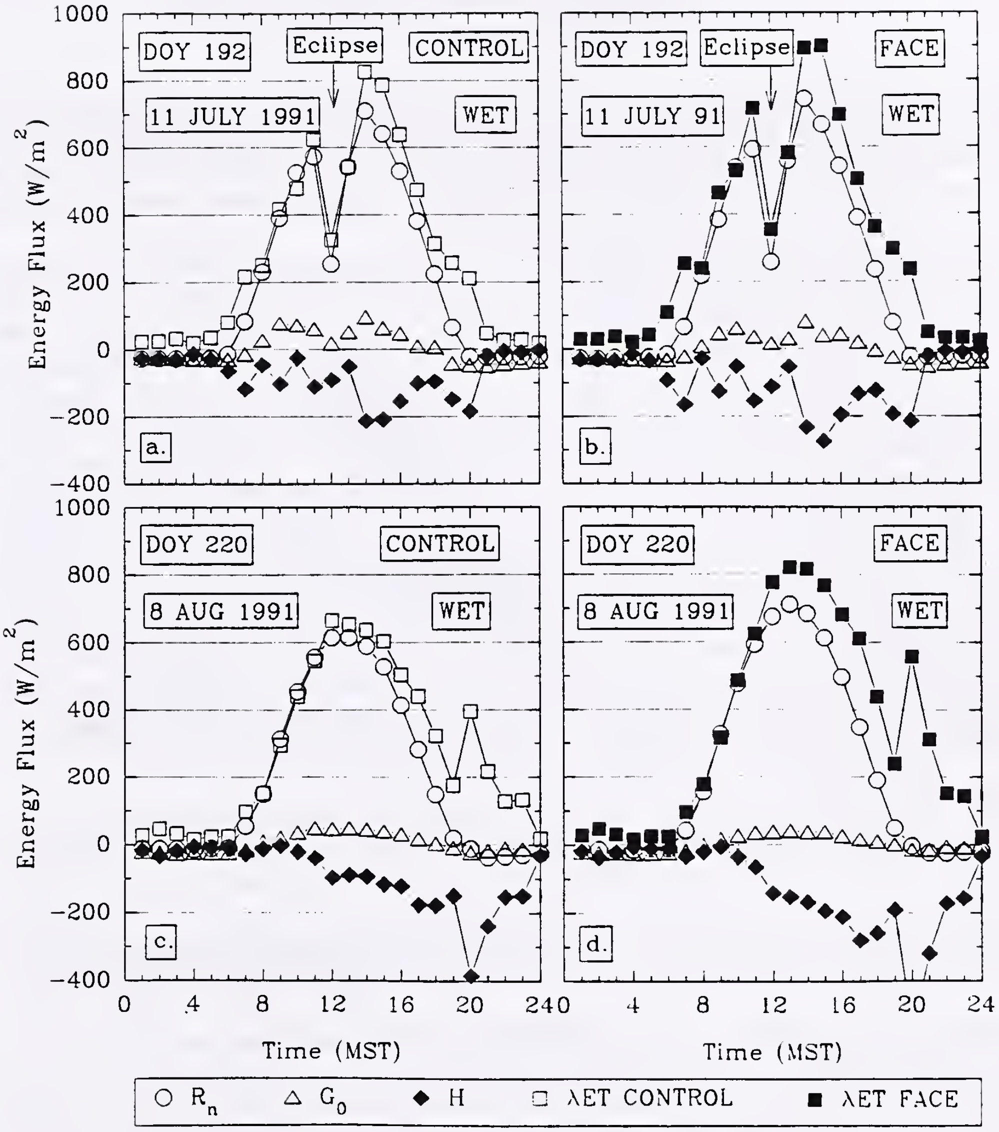

Figure 1. Energy balance components for the (a) ambient CO_2 (CONTROL) plots versus time of day for DOY 192 and (c) also for DOY 220. Similarly, (b) the components for the 550 μmol/mol CO_2 (FACE) plots on DOY 192 and (d) on DOY 220. The energy fluxes include net radiation, $\underline{R_n}$; surface soil heat flux, $\underline{G_o}$; sensible heat flux, $\underline{H}$, and latent heat flux, $\underline{\lambda ET}$. The values are averages of replicates 1 and 2.

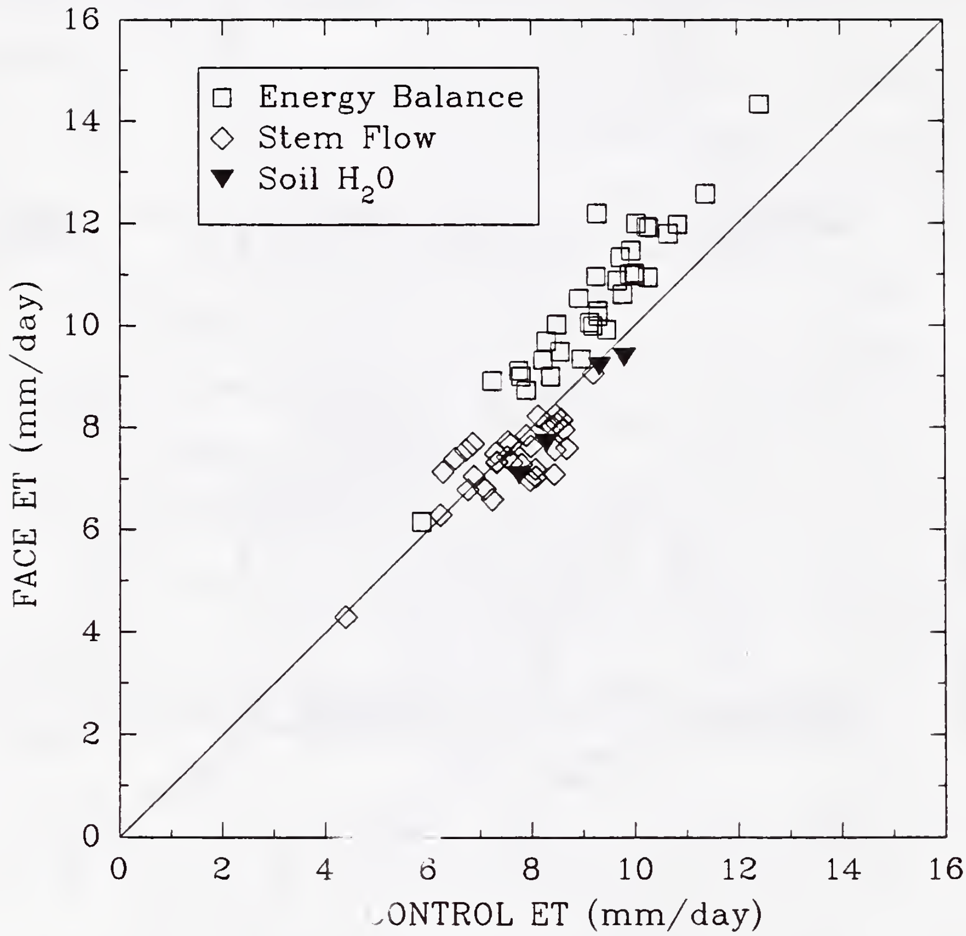

Figure 2. Daily evapotranspiration, ET, from FACE plots versus the corresponding values from the central plots for three methods of determination in energy balance (this report), stem flow gauges (Dugas et al., submitted), and soil water balance (Hunsaker et al., submitted).

PROGRESS AND PLANS FOR THE FREE-AIR CO_2 ENRICHMENT (FACE) PROJECT

Bruce A. Kimball, Supervisory Soil Scientist;
Paul J. Pinter, Jr., Research Biologist;
Gerard W. Wall, Plant Physiologist;
Richard L. Garcia, Plant Physiologist;
Douglas J. Hunsaker, Agricultural Engineer;
Francis S. Nakayama, Research Chemist; and
Sherwood B. Idso, Research Physicist

PROBLEM: The CO_2 concentration of the atmosphere is increasing and expected to double sometime during the next century. Climate modelers have predicted that the increase in CO_2 will cause the Earth to warm and precipitation patterns to be altered. This project seeks to determine the effects of such an increase in CO_2 concentration and any concomitant climate change on the future productivity, physiology, and water use of crops.

APPROACH: Numerous CO_2-enrichment studies in greenhouses and growth chambers have suggested that growth of most plants should increase about 30%, on the average, with a projected doubling of the atmospheric CO_2 concentration. However, the applicability of such work to the growth of plants outdoors under less ideal conditions has been seriously questioned. The only approach whose realism is unquestioned and which can produce an environment as representative of future fields as possible is the free-air CO_2 enrichment (FACE) approach.

The FACE approach has been criticized, because the prodigious quantities of CO_2 required make it expensive. A FACE experiment is expensive, but because of the relatively large area of the FACE plots, there is a huge economy of scale, so that, per unit of treated plant material, FACE costs 1/4 or even less than other approaches. Thus, there is an economic incentive to have many scientists cooperate on large, comprehensive FACE experiments.

About 20 scientists from ARS, Brookhaven National Laboratory, and several universities have cooperated on a FACE project for the past three years at The University of Arizona's Maricopa Agricultural Center (MAC). These experiments have yielded a wealth of information about the growth and physiological responses of cotton to elevated CO_2, with ample and limiting supplies of water. A 17-chapter book, *FACE: Free-Air CO_2 Enrichment for Plant Research in the Field*, was published in 1991, covering the FACE work up through 1989, and about 20 manuscripts have been prepared for a special issue of *Agricultural and Forest Meteorology,* covering the 1990 and 1991 cotton experiments. Data sets in IBSNAT format suitable for validation of plant-growth models have been prepared.

FINDINGS: It is beyond the scope of this report to review the results presented in the numerous above-mentioned manuscripts. Briefly, however, averaged over three years, cotton yields were increased about 40% with CO_2 concentrations elevated to 550 ppm, and there was no significant increase in water use.

INTERPRETATION: The increasing atmospheric CO_2 concentration should be beneficial to future cotton growers, provided water supplies do not change significantly.

FUTURE PLANS: A FACE wheat experiment commenced in December 1992, with final harvest expected near the end of May 1993. CO_2 levels of 550 μmol/mol and ambient are used, and well-watered and water-stress irrigation treatments are included. About 25 scientists from 6 ARS locations, 5 universities, 3 other laboratories, and 4 foreign countries plan to participate. Measurements will include above-and below-ground biomass and yield, height, leaf area, morphology, stomatal density, anatomy, carbohydrates, digestibility, grain quality, elemental content, soil and plant-carbon isotopes, evapotranspiration, canopy temperature, soil-water content, soil respiration, decomposition, photosynthesis, respiration, photosynthetic proteins, chlorophyll, reflectance and light use efficiency, leaf spectral characteristics and pigments, and insect populations. Three or more wheat modelers will also participate.

COOPERATORS:

Brookhaven National Laboratory
  S. Long, G. Nie, G. Hendrey, K. Lewin, J. Nagy
Colorado State University
  W. Hunt
Free University of Amsterdam
  H. Vugts, J. Rozema, M. Groen, A. Frumau, P. Gak
Grassland Protection Research (USDA-ARS, Temple, Tx)
  H. Johnson
Institute of Environmental Analysis and Remote Sensing
  for Agricualture (Florence) Italy
  A. Giuntoli, F. Miglietta
Institut de Recerca i Technologia Agroalimentaries (Barcelona) Spain
  M. Estiarte, J. Penuelas
Kansas State University
  J. Ham
Manhattan College
  L. Evans
Michigan State University
  E. Paul
National Soil Dynamics Laboratory
  H. Rogers
NASA-Ames Research Center
  D. Peterson
Potsdam Institute for Climate
  T. Kartschall, F. Wechsung, G. Wechsung
Russell Research Center (USDA-ARS)
  D. Akin
University of Alberta
  R. Grant
University of Arizona
  R. Rauschkolb, S. Leavitt, D. Fangmeier
University of Florida (USDA-ARS)
  L. Allen, J. Vu, T. Sinclair
U. S. Salinity Laboratory
  D. Suarez
U. S. Water Conservation Laboratory
  P. Pinter, F. Nakayama, G. Wall, R. Garcia, S. Idso
Western Cotton Research Laboratory
  J. Mauney, D. Hendrix, D. Akey, J. Radin, N. Bhattacharya
Western Wheat Quality Laboratory (USDA-ARS)
  C. Morris
Woods Hole Research Center
  J. Amthor

EFFECTS OF SUBSURFACE IRRIGATION TUBE SPACING, TILLAGE PRACTICES, AND ROW SPACING IN WHEAT

Paul J. Pinter, Jr., Research Biologist;
Gary Wall, Plant Physiologist;
Richard Garcia, Plant Physiologist;
Bruce A. Kimball, Supervisory Soil Scientist; and
Robert LaMorte, Civil Engineer

PROBLEM: In anticipation of a large scale, Free-Air Carbon dioxide Enrichment (FACE) project during the 1992-93 growing season, we conducted a preliminary experiment with wheat on the demonstration farm at The University of Arizona's Maricopa Agricultural Center. Our objectives for conducting this exercise were to: 1) examine problems that might occur when wheat is grown using subsurface drip irrigation, 2) select an appropriate cultivar for our studies 3) evaluate effect of bed and furrow planting procedures used with drip irrigation, and 4) develop procedures for plant sampling and growth analysis. This exercise was also intended to help us meet goals for the upcoming FACE experiment by familiarizing our personnel with wheat growth and development.

APPROACH: The experiment was conducted in the same field where FACE experimentation on cotton had been carried out during the previous three years using subsurface drip irrigation at 1.02 m spacing. Additional irrigation tubing was installed in part of the field to achieve a second treatment spacing of 0.51 m. Following local convention for growing a wheat crop after cotton using drip irrigation, a ridge and furrow, soil tillage system was preserved. Two hard red, spring wheat cultivars (Yecora rojo and Baker) were planted on 20-21 January 1992, about 2 months later than normal because of inclement weather, and equipment availability. Two plant row spacings were tested (0.15 m and 0.30 m) at a target seeding rate of 157 kg ha^{-2}. Treatment combinations were replicated three times. Seedling emergence for Yecora rojo was determined by counting plants in five separate, one-meter-long segments of row in each treatment on 20 February 92. Growth and development of Yecora rojo were measured at biweekly intervals for all treatments. Data were tabulated separately for plants growing in bed and furrow positions. Final yield was determined using a small plot combine to harvest all treatments and replicates of both cultivars.

FINDINGS: There were no significant differences in seedling populations between wide and narrow drip tube spacings or replicates. The wider plant row spacing was effected by blocking alternate seed hoppers of a conventional grain drill having 0.15 m spacing and by opening the seed aperture slightly. This procedure resulted in an unintentional, albeit significantly different ($p < 0.05$), density of seedlings between the 0.15 m and 0.30 m row spacings [334 $\pm$ 13 (se) and 240 $\pm$ 17 plants m^{-2}, respectively]. Experimental treatments and plant position, (i.e. bed versus furrow), had a large effect on growth, tillering, and biomass of Yecora rojo. For example, during mid-to late May 1992, plant sampling revealed that wheat grown on the narrow drip tube spacing matured slower but had 18% more biomass than plants grown on the wider spaced tubes. Individual plants on the tops of soil beds in the narrow drip tube spacing were 16% larger and had 18% more heads than plants growing in the furrows. The difference in growth between bed and furrow was exaggerated in the wider drip spacing. Plants growing on the bed directly above a drip tube were 79% larger and had 38% more heads than plants in the furrow, which were about 0.5 m distant from the nearest drip tube. This type of spatial variation would probably not justify doubling the number of drip tubes in a commercial stand, but would be very difficult to accommodate in a rigorous scientific sampling scheme.

Final yields (Table 1) mirrored patterns seen in the late season plant sampling. Highest yields in both cultivars occurred in narrow (0.15 m) row spacing and narrow (0.51 m) spacing between subsurface drip tubing. Lowest yields were associated with the wide plant row spacing and wide drip tube spacing. When averaged over all our treatments, final grain yield of Yecora rojo was 8.5% greater than the yield of Baker, a locally grown cultivar, indicating that it performs competitively in the Maricopa area. Grain yields of Yecora rojo from the narrow drip tube spacing were 54% greater than yields from the wider spacing. The 0.15 m plant row spacing increased grain yield 38% over the 0.30 m row spacing. However, this finding was not deemed biologically significant because

of initial higher seedling population (as determined by emergence counts) in the 0.15 m spacing and because of the late planting date which reduced the tillering potential of 0.30 m spacing.

INTERPRETATION: The 1992 preliminary wheat experiment provided useful information regarding the culture of spring wheat in a drip irrigation setting. Based on acceptable growth and yield of Yecora rojo in this test, our recommendation is to plant that cultivar in the 1992-1993 FACE wheat experiment. Additional advantages include its widespread geographic utilization, previous knowledge of its growth, water use and reflectance characteristics, and a reduction in problems with volunteer plants in the FACE experiment. An important finding was that 1.02 m-wide irrigation drip tubing spacing caused undesirable variation in individual plant growth and development, depending on distance from the drip tube source and position in the ridge furrow system. Therefore our recommendation is to conduct the upcoming FACE experiment using narrow spacing (0.51 m) between buried drip tubes. It is also desirable to plant seed at an intermediate row spacing of 0.25 m, which should provide optimum expression of plant tillering patterns, allow sufficient room to walk between rows for sampling purposes, and maintain symmetry with 0.51 m drip tube spacing. Planting on a flat seed bed will suppress variation attendant upon the ridge and furrow system.

We wish to thank Ms. Carrie O'Brien, Mr. Ric Rokey and Mr. Ron Seay, Technicians from the University of Arizona and USDA/ARS U.S. Water Conservation Laboratory for field work and processing of plant samples.

Table 1. Final grain yields of Yecora rojo and Baker wheat grown on the drip irrigation system at the Maricopa Agricultural Center. Yield estimates are based on field dried grain weights.

		FINAL GRAIN YIELDS (1000 kg ha^{-1})			
		Narrow Row Spacing (0.15 m)		Wide Row Spacing (0.30 m)	
		Narrow Drip (0.51 m)	Wide Drip (1.02 m)	Narrow Drip (0.51 m)	Wide Drip (1.02 m)
'BAKER'	Mean	5.91	4.48	5.21	2.24
	std. err.	0.42	0.27	0.01	0.25
'YECORA ROJO'	Mean	6.31	4.92	5.42	2.71
	std. err.	0.14	0.26	0.23	0.21

CO_2 ENRICHMENT OF PINE TREES

R. L. Garcia, Plant Physiologist;
S. B. Idso, Research Physicist; and
B. A. Kimball, Supervisory Soil Scientist

PROBLEM: As the air's CO_2 content continues to rise, it is becoming increasingly urgent that we document the effects of this phenomenon on the biosphere. An important component of this research effort has been directed to determining the consequences of long-term exposure of trees to elevated levels of CO_2. Central to the productivity of any plant or plant community are the processes associated with gas exchange. In this regard, we sought to answer the question: Do the positive effects of atmospheric CO_2 enrichment on whole-tree net carbon assimilation decline with time, or do they remain constant or even rise?

APPROACH: In early March 1991, a number of 40-cm-tall *Pinus eldarica* L. seedlings were planted in a field of avondale loam at Phoenix, Arizona. Each was surrounded by a clear-plastic-wall open-top enclosure through which air was circulated at a rate of four enclosure-volume exchanges per minute. Two of the trees were continuously exposed to ambient air averaging 402 μL of CO_2 per L of air ($\mu L\ L^{-1}$), while two of them grew in CO_2-enriched air of 550, 678, and 788 $\mu L\ L^{-1}$. All trees were irrigated and fertilized to minimize any moisture or nutrient stress and maintained under these conditions for a period of 15 months, after which their net CO_2 exchange rates were measured with a continuous-flow gas exchange system of the type developed by Garcia *et al.*, 1990.

FINDINGS:
1) After 15 months, the trees grown under 788 $\mu L\ L^{-1}$ CO_2 had 3.5 times the bole volume and 3.6 times photosynthetic rate of trees grown under ambient conditions (Table 1).
2) When exposed to short-term CO_2 enrichment of 788 $\mu L\ L^{-1}$, trees grown under ambient conditions (about 360 $\mu L\ L^{-1}$) responded with a doubling of photosynthetic rates (Table 1).
3) In short-term CO_2 response evaluations, carbon uptake rates, of low CO_2-treatment trees saturated at approximately 5 times their ambient concentration rates, while rates of the high CO_2-treatment trees rose linearly across the entire CO_2 range investigated to 10 times their ambient concentration rates (Figure 1).

INTERPRETATION: Solitary pine trees grown under optimum water and nutrient conditions are very sensitive to atmospheric CO_2 concentrations while they are in seedling- and juvenile-growth stages. However, the enhanced production of foliage induced by CO_2 enrichment results in increased self-shading which, in turn, may moderate the long-term impact of CO_2 enrichment. Our findings also suggest that long-term exposure to elevated CO_2 can increase the ability of pine trees grown under these conditions to respond positively to still higher CO_2 concentrations.

FUTURE PLANS:
1) We hope to make measurements similar to those reported here during the winter months, in order to examine the interaction effects of temperature and CO_2 enrichment on the photosynthetic processes.
2) It would be of interest to design a study to evaluate the effects of "super-enrichment" of CO_2 on pine tree growth, in order to confirm our photosynthesis response work.
3) To date, our work has focused on the response to CO_2 enrichment of solitary trees grown under conditions of optimum water and nutrients. It would be valuable to apply our techniques to a community of trees grown under non-optimum conditions.

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Garcia, R.L., S.B. Idso, and B.A. Kimball. 1993. Net photosynthesis as a function of carbon dioxide concentration in pine trees grown at ambient and elevated CO_2. In preparation.

Garcia, R., J.M. Norman, and D.K. McDermitt. 1990. Measurements of canopy gas exchange using an open chamber system. Remote Sensing Reviews 5(1):141-162.

Table 1. Data and calculations pertaining to the evaluation of the compound interest effect of atmospheric CO_2 enrichment in solitary Eldarica Pine trees

Atmospheric CO_2 concentration (μL L-1)	402	552	702	852
1. Typical daylight totals of P (mol CO_2 tree^{-1})	0.677	1.394	1.977	2.436
2. Normalized (relative to 402 μL L^{-1}) totals of P	1.00	2.06	2.92	3.60
3. P of ambient-treatment tree (μmol CO_2 tree^{-1}s^{-1})	12.85	18.65	24.46	30.26
4. Normalized (relative to 402 μL L^{-1}) ambient-tree P	1.00	1.45	1.90	2.35
5. Compound interest effect: Line 2 ÷ Line 4	1.00	1.42	1.54	1.53
Atmospheric CO_2 concentration (μL L^{-1})	402	550	678	788
6. Bole volumes of trees (L)	0.234	0.445	0.685	0.815
7. Normalized (relative to 402 μL L^{-1}) bole volumes	1.00	1.90	2.93	3.48
8. P of ambient-treatment tree (μmol CO_2 tree^{-1}s^{-1})	12.85	18.58	23.53	27.78
9. Normalized (relative to 402 μL L^{-1}) ambient-tree P	1.00	1.45	1.83	2.16
10. Compound interest effect: Line 7 ÷ Line 9	1.00	1.31	1.60	1.61

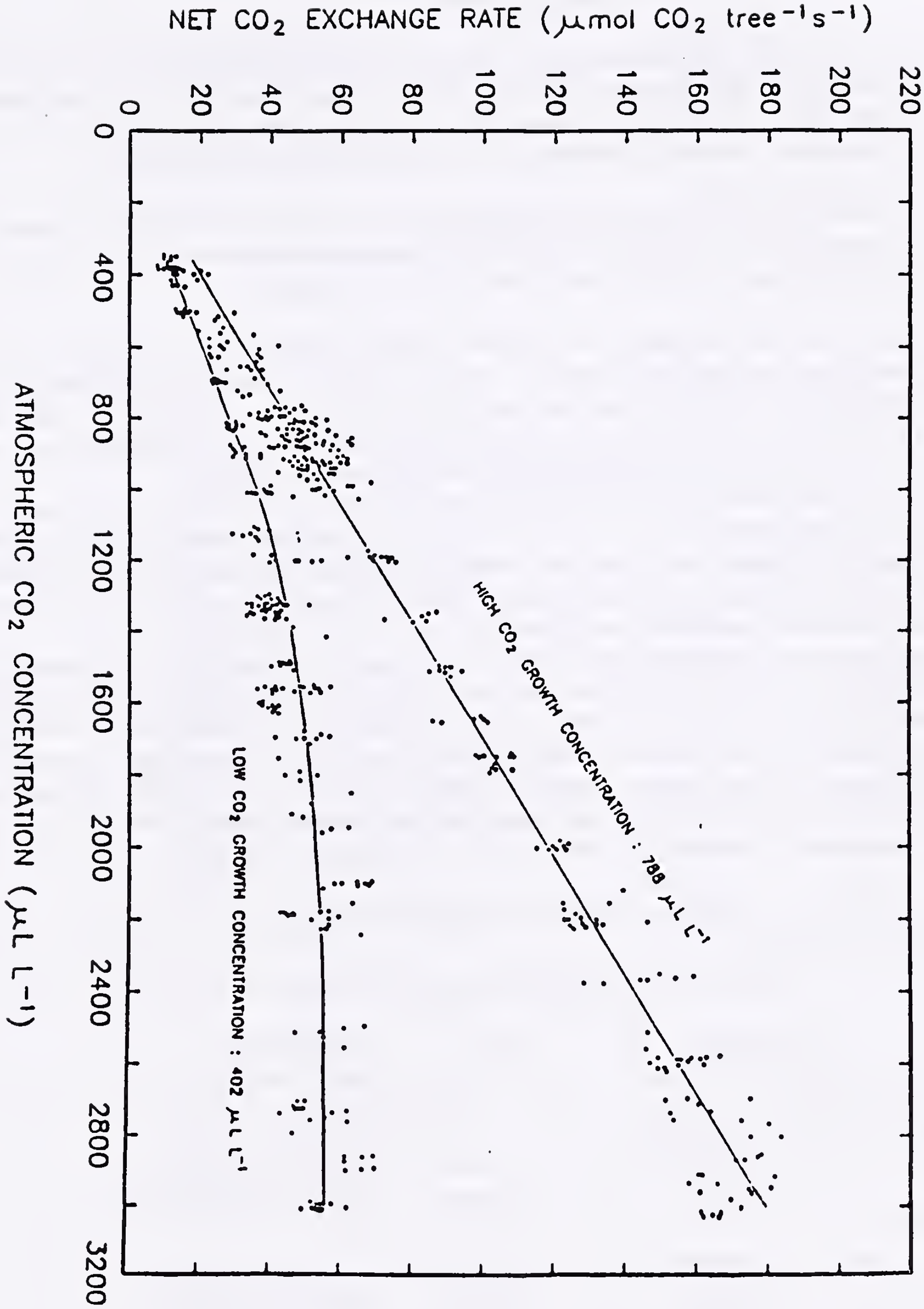

Figure 1. Net CO_2 exchange rate vs. atmospheric CO_2 concentration for *Pinus eldarica* trees grown for 15 months at CO_2 concentrations of 402 and 788 $\mu L\ L^{-1}$.

SOIL CARBON DIOXIDE FLUXES IN NATURAL AND FREE-AIR CO_2 ENRICHED SYSTEMS

F.S. Nakayama, Research Chemist

PROBLEM: The rate of soil-carbon-dioxide release from the soil gives an indication of root and microbial activities in the soil profile. This flux has significant effects on "greenhouse gases" and the overall carbon balance of the atmosphere. The object of this study is to determine the soil CO_2 fluxes in both natural and CO_2-enriched systems that can be used for carbon balance modeling and field photosynthesis measurements.

APPROACH: Soil carbon-dioxide fluxes will be determined in conjunction with the free-air release of carbon dioxide enrichment system (FACE). Gas samples will be taken at the various treatment combinations of CO_2 and irrigation. Detailed statistical analyses will be made for the flux measurements.

FINDINGS: Sample and statistical analyses of the carbon-dioxide flux measurements were completed for the 1991 experiment which ran from May through November. This experiment consisted of four check and four CO_2 enriched open air released sites. The individual sampling sites also included "wet" and "dry" water treatments. Water applications in the dry treatment were based on 2/3 of the wet treatment. Four sampling chambers for each water x CO_2 levels x four replicates were used for a total of 64 flux sampling sites.

An example of soil CO_2 flux behavior for the FACE-WET and CONTROL-WET treatment combinations is shown in Figure 1. The daily flux values ranged from 3 to 8 $\mu mol/m^2/s$ during the late August to early September period. The fluxes for the FACE treatments were higher than the CONTROL, except in the FACE-DRY that was lower than the CONTROL-WET. Moisture levels tended to overshadow CO_2 enrichment. The CO_2 effect persisted for approximately 30 days after the enrichment was terminated.

Statistical analysis based on the split-plot design showed significant differences in CO_2 and irrigation levels for the 22 May to 16 September (DAY 142 to 259) treatment period (Table 1). A comparison of fluxes measured from 18 September through 16 October (DAY 260 to 289), after the CO_2 was turned off in September, continued to show the effect of CO_2 enrichment on flux (Table 2), with interactions of CO_2 with H_2O and the water-level treatment remained highly significant. The only treatment effect beyond this interval to 05 November 1991, the last sampling date, was the water level. The flux values for the October through November period were about one-half that of the preceding intervals, possibly the result of lower plant root and microbial activities.

Table 1. Analysis of CO_2 enrichment and irrigation treatment effects on soil CO_2 fluxes for the 22 May - 16 September 1991 period.

Source	SS	df	MS	F	P
Main plots					
Blocks	116.9673	33	3.5445		
CO_2	18.6776	1	18.6776	69.0807	0.0000 ***
Main plot error	8.9224	33	0.1703		
H_2O	10.0661	1	10.0662	48.2361	0.0000 ***
H_2O x CO_2	1.1306	1	1.1306	5.4177	0.0230 *
Error	28.6453	66	0.4340		
Total	169.5374	135			

Table 2. Analyses of the CO_2 enrichment and irrigation treatment effects on soil CO_2 fluxes for three periods--Duncan's Multiple Range Test.

Duncan's Multiple Range Test (22 May - 16 Sept. 1991)

FACTOR: H_2O
Error mean square = 0.2087
Degrees of freedom = 66
Significance level = 5%
LSD, 0.05 = 0.1564

Treat.	Mean
WET	3.92 a
DRY	3.37 b

FACTOR: CO_2
Error mean square = 0.2704
Degrees of freedom = 33
Significance level = 5%
LSD, 0.05 = 0.1814

Treat.	Mean
FACE	4.02 a
CHECK	3.28 b

Duncan's Multiple Range Test (18 Sept. - 16 Oct. 1991)

FACTOR: H_2O
Error mean square = 0.1017
Degrees of freedom = 18
Significance level = 5%
LSD, 0.05 = 0.2119

Treat.	Mean
WET	4.19 a
DRY	3.31 b

FACTOR: CO_2
Error mean square = 0.1293
Degrees of freedom = 9
Significance level = 5%
LSD, 0.05 = 0.2573

Treat.	Mean
FACE	3.90 a
CHECK	3.60 b

Duncan's Multiple Range Test (18 Oct. - 05 Nov. 1991)

FACTOR: H_2O
Error mean square = 0.1088
Degrees of freedom = 8
Significance level = 5%
LSD, 0.05 = 0.3401

Treat.	Mean
WET	1.73 a
DRY	1.32 b

FACTOR: CO_2
Error mean square = 0.0418
Degrees of freedom = 4
Significance level = 5%
LSD, 0.05 = 0.2537

Treat.	Mean
FACE	1.53 a
CHECK	1.52 a

INTERPRETATION: Significantly larger soil-carbon-dioxide fluxes were present in the free-air CO_2 enriched treatments than the untreated plots. Higher irrigation levels also caused higher flux. An interaction was also present with the CO_2 and H_2O levels. Thus, the higher physiological activities in the soil would contribute to these observations and would indicate that a biological buildup in carbon is occurring with the increase in CO_2 levels.

FUTURE PLANS: Soil carbon dioxide fluxes in the FACE experiment will be determined on wheat following procedures similar to the cotton study. Carbon dioxide concentration in the soil gases at different depths may be measured for modelling CO_2 distribution in the soil profile and fluxes from the soil surface.

Figure 1. Comparison of the soil fluxes (μmol/m^2/s) for the wet plots in the FACE and CONTROL treatments.

MODULAR STRUCTURE OF COTCO2

G.W. Wall, Plant Physiologist; and
B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The concentration of carbon dioxide in the atmosphere continues to rise. A need exists, therefore, to identify the major sources and sinks of CO_2 and to elucidate the effect they will have on terrestrial vegetation. Projected global surface temperature deviations due to increases in atmospheric concentrations of radiative "greenhouse" gases may cause spatial shifts in the location of Earth's major biomes. This could disrupt major agricultural areas and human demographics on a global scale. Because uncertainties exist with respect to how global change will ultimately influence terrestrial vegetation, it is imperative to investigate these complex interactions. Experimentation, although a useful endeavor, cannot encompass all the environmental parameters which must be considered in such a complex system. It is possible, however, to identify system behavior experimentally and construct models which will predict system response to a changing environment.

APPROACH: In conjunction with the Free-Air-CO_2-Enrichment (FACE) project, a new, physiologically-based, mechanistic, modular-structured simulation model of cotton (*Gossypium hirsutum* L.) physiology, growth, development, and productivity has been constructed (Amthor and Kimball, 1990a,b). Model development, as a component of the overall FACE project, has assisted in identifying the required alterations in system design to ensure that appropriate databases are derived experimentally. Since the model must extrapolate beyond the available model development databases, explicit physiological mechanisms were used to minimize reliance on empirical relationships. The model is named COTCO2 for cotton response to atmospheric concentration of CO_2 (Wall et al., 1993).

Whenever possible, a modular structure was used in the development of COTCO2. Once validated, modular components which simulate a particular physiological process can be used in larger scale global modeling efforts. A modular structure facilitates updating algorithms once our understanding of a particular mechanism governing a physical or physiological process unfolds. Furthermore, modules of various sophistication can be interchanged to quantitatively assess the level of complexity required to obtain reliable simulated output for a given process.

In its present configuration, COTCO2 consists of nine separate modules: COTCO2, INITAL, GEMRGE, ENVIRN, CANOPY FIZIOL, LEAF FIZIOL, GROWTH, DROUT, DAYOUT which contain seventy subroutines, thirteen functions, and three common block include files, involving over 1000 variables and parameters in approximately 3000 lines of executable ANSI FORTRAN 77 code. The overall modular structure of COTCO2 is illustrated in Figure 1. It consists of a main control module, COTCO2, which, in turn, will call all other modules. Initialization of all variables and parameters occurs in INITAL, germination of the seed occurs in GEMRGE, and determination of the status of the microclimate is occurs in the ENVIRN module. Plant physiological processes are simulated in the CANOPY and LEAF FIZIOL modules. Individual organ growth occurs in the GROWTH module. Output of diurnal and daily values of state variables occur in the DROUT and DAYOUT modules, respectively. Table 1 contains a list of all the subroutines, functions, common block include files, and mathematical and physical constant files, and a general description of their content and the module in which they are referenced.

FINDINGS: A working version of COTCO2 exists. Run-time for a season-long simulation on a Sun Microsystem SPARC station-2 workstation is about thirty minutes. Experimental databases derived from cotton cultivar Delta Pine 77, grown in ambient air and air enriched to a CO_2 concentration of 550 μL L^{-1} with FACE technology during the 1989 through 1991 growing seasons have been compared to simulated output. Experimental results from Open-Top-Chamber (OTC) (1983-1987) and Soil-Plant-Atmosphere-Research (SPAR) studies (1990) have also been compared to simulated results. Although not expressed quantitatively herein, model validation indicates that the basic structure of the model is sound. Preliminary results indicate that alterations in parameters and response functions are required, particularly those which pertain to growth of organs and partitioning of assimilates.

INTERPRETATION: Continued model development, validation with real-world databases, and comprehensive sensitivity analysis are required. Application of COTCO2 in larger scale global impact analysis is feasible once reliable predictions are obtained.

FUTURE PLANS: Model development, documentation, and validation will continue. Cultivar specific parameters and response functions need to be developed, particularly those which pertain to growth and partitioning of assimilates. A sensitivity analysis to test model performance, with respect to the most influential parameters, needs to be performed.

Once completed, COTCO2 will enable predictions of cotton production over a broad ecological range, while providing the means to predict the impact of change in atmospheric CO_2 concentrations and any associated potential climate change on global cotton production. Ultimately, it will aid in the development of strategies to mitigate the adverse effects of global change, while optimizing those that are beneficial.

COOPERATORS: Dr. J.S. Amthor, The Woods Hole Research Center, 13 Church Street, P.O. Box 296, Woods Hole, MA, 02543.

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Table 1. Summary of subroutines, functions, include files, and modular structure of COTCO2

NAME	DESCRIPTION	MODULE
COTCO2	Main Control Algorithm	COTCO2
DUNCAN	Canopy-Shortwave Radiation Interactions	COTCO2
INSECT	Damage to Leaves and Squares by Insect Herbivores	COTCO2
INITAL	Initialize Variables	INITAL
LISTID	Reads PathInc File to Identify IBSNAT Input Files	INITAL
PARMIN	Parameter Input File, Table Look-up Response Functions	INITAL
PARAMO	Listing of Parameters for COTCO2 Run-Banner Page	INITAL
PDV001	Quantitative Biochemistry of Biosynthesis	INITAL
PDVOUT	Output Table of Biosynthetic Parameters	INITAL
READDA	Reads Input Files and Interfaces with COTCO2	INITAL
RETRVE	Control Algorithm for IBSNAT Input Files	INITAL
VALFAB	Reads IBSNAT Validation Input File	INITAL
DISTRT	Mass and Distribution of Root System in Soil Cells	GROWTH
DISTST	Stem Segment-Mass Distribution	GROWTH
GEMRGE	Germination and Growth to Emergence	GEMRGE
GROWFR	Fruit Growth	GROWTH
GROWLF	Cotton Leaf Growth	GROWTH
GROWMR	Growth of Meristem	GROWTH
GROWRT	Growth of Taproot and Lateral Roots	GROWTH
GROWST	Growth of Stem Segment	GROWTH
GROWTH	Control Algorithm for Organ Growth	GROWTH
CANVP	Vapor Pressure of Air in Canopy Layer	ENVIRN
DARCY	Darcian Flow of Water Among Soil Cells, Surface Energy Balance Evaporation, Soil Heat Flow, and Soil Temperature	ENVIRN
ENVIRN	Air and Soil Physical Conditions of Microclimate	ENVIRN
FIELDC	Distribution of Irrigation or Rain Water	ENVIRN
LFLOCA	Location of Leaves and Leaf-Area Indices Within Canopy Layers	ENVIRN
PROFWD	Profile of Wind Speed Above and Within the Canopy	ENVIRN
SOILN	Soil-Nitrogen Transformation	ENVIRN
SOLARI	Sun/Earth Geometry and Solar Radiation at Top of Canopy	ENVIRN
SURFAC	Steady-State Soil Surface Energy Balance	ENVIRN
UPTAKE	Water and NO_3 Uptake by Roots	ENVIRN
CANFIZ	Physiology Within Canopy Layer	FIZIOL CANOPY
FIZIOL	Plant Control Algorithm for Plant Physiology	FIZIOL CANOPY
MRFRUT	Maintenance Respiration by Fruit Tissue	FIZIOL CANOPY
MRROOT	Maintenance Respiration by the Root Tissue	FIZIOL CANOPY
MRSTEM	Maintenance Respiration by Stem Tissue	FIZIOL CANOPY
PROFLW	Long Wave Radiation Absorbed by Leaves in Canopy Layers	FIZIOL CANOPY
REDIST	Redistribution of Phloem Among Organs	FIZIOL CANOPY
SNSCRT	Senescence of Lateral Roots	FIZIOL CANOPY
BLAYER	Leaf Boundary-Layer Characteristics	FIZIOL LEAF
FRQHR1	Farquhar's Photosynthesis Model	FIZIOL LEAF
FRQHR2	"Internal" Part of Farquhar's Photosynthesis Model	FIZIOL LEAF
LEAFEB	Leaf Equilibrium Energy Budget and Temperature	FIZIOL LEAF
MRLEAF	Leaf Blade Maintenance Respiration Rate	FIZIOL LEAF
PHYSLF	Leaf Physiology Control Algorithm for Leaf Physiology	FIZIOL LEAF
PLOAD	Phloem Loading and Associated Respiration	FIZIOL LEAF
STCOND	Empirical Equations for GSH20 (Inital Guess)	FIZIOL LEAF

Table 1. (cont.)

NAME	DESCRIPTION	MODULE
DIURNL	Output of Diurnal ASCII Files	DROUT
DROUT	Control Algorithm for Diurnal Output	DROUT
MAPLWR	Map of Long Wave Radiation Fluxes Above, In, and Below Canopy	DROUT
MAPSQS	Map of Square Sugar Content	DROUT
MAPSWV	Map of Absorption of Short Wave Radiation in Canopy Layers	DROUT
MAPWND	Map of Wind Speed Profile Through the Canopy	DROUT
DAILY	Output of Daily ASCII Files	DAYOUT
DAYOUT	Control Algorithm for Daily Output	DAYOUT
MAPFRM	Map of Fruit Structural Masses	DAYOUT
MAPFRT	Map of Fruit Developmental Stage and Distribution	DAYOUT
MAPLA	Map of Leaf Area	DAYOUT
MAPLMT	Map of Limitation to Root Growth in Each Soil Cell of Half Slab	DAYOUT
MAPNO3	Map of Soil-Cell-Nitrate Content	DAYOUT
MAPRT	Map of Root-Mass Distribution	DAYOUT
MAPSAB	Map of Stem-Mass Above Each Stem Segment	DAYOUT
MAPST	Map of Soil Temperature in Each Layer	DAYOUT
MAPSTL	Map of Stem-Segment Lengths	DAYOUT
MAPSWC	Map of Soil Cell Volumetric Water Content	DAYOUT
MAPSWP	Map of Soil Cell Matrix Potential	DAYOUT
STATPL	Output Some Current Values of Accumulators	DROUT/DAYOUT
CARBON	Cumulative Carbon Balance	DROUT/DAYOUT
SHOOT	Structural Mass of Shoot Organs by Type Carbon and Nitrogen Contents of Shoot Structural Mass	DROUT/DAYOUT
ALLSUG	Whole-Plant Soluble Sugar Content	DROUT/DAYOUT
RTPLOT	Run-Time Graphics	DROUT/DAYOUT
ABSHUM	Absolute Humidity	FUNCTION
AIRTMP	Air Temperature (C or K) from Time of Day and Daily Maximum and Minimum Temperatures	FUNCTION
CDATE	Convert Integer Day/Year to Character Month/Day	FUNCTION
CONEH	Height of Right Circular Cone from Radius at Base and Volume	FUNCTION
CONER	Basal Radius of Right Circular Cone from Height and Volume	FUNCTION
CONEV	Volume of Right Circular Cone from Height and Base Radius	FUNCTION
DEEPST	Deep Soil (Below Bottom Layer) Temperature	FUNCTION
LATENT	Latent Heat of Vaporization	FUNCTION
LINTRP	Linear Interpolation of X-Y Values	FUNCTION
RELRAT	Rate Relative, Based on the Arrhenius Equation	FUNCTION
RESPTF	Relative Respiration Rate Temperature Factor	FUNCTION
SLAYER	Soil Layer in Which a Depth (M) Occurs	FUNCTION
SVP	Saturation Vapor Pressure of Water	FUNCTION
CNSTNT	Mathematical and Physical Constants Include File	COMMON
COTCO2.INC	Include File with Named Common Blocks	COMMON
LEAFFIZ.INC	Leaf Physiology Include File	COMMON

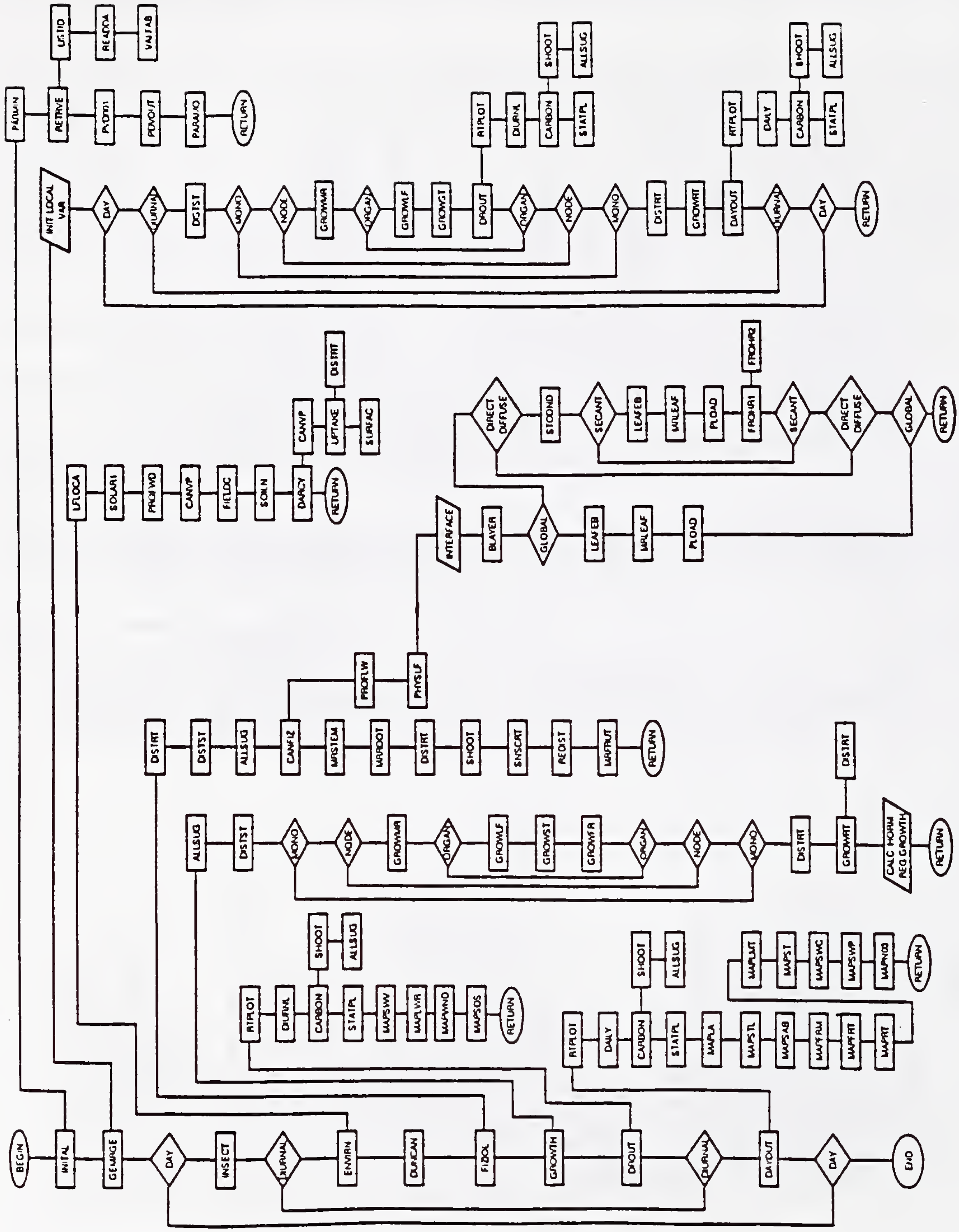

Figure 1. Flow diagram of COTCO2

EVALUATING PLANT DYNAMICS AS RELATED TO WATER CONSERVATION AND CLIMATE CHANGE USING REMOTE SENSING

CO_2 ENRICHMENT OF TREES

S.B. Idso, Research Physicist; and
B.A. Kimball, Supervisory Soil Scientist

PROBLEM: The continuing rise in the CO_2 content of Earth's atmosphere is believed by many people to be the most significant ecological problem ever faced by mankind, due to the widespread assumption that it will lead to catastrophic global warming via intensification of the planet's natural greenhouse effect. However, this belief is largely due to a lack of knowledge of the many beneficial effects of atmospheric CO_2 enrichment on Earth's plant life. Hence, it is imperative that this other aspect of atmospheric CO_2 enrichment be elucidated, so that the public can have access to the full spectrum of information about the environmental consequences of higher-than-ambient levels of atmospheric CO_2. Only under such conditions of complete and wide-ranging understanding can the best decisions be made relative to national and international energy policies.

As forests account for two-thirds of global photosynthesis and are thus the primary player in the global biological cycling of carbon, we have chosen to concentrate on trees within this context. Specifically, we seek to determine the direct effects of atmospheric CO_2 enrichment on all aspects of their growth and development; and we hope to be able to determine the ramifications of these direct effects for global carbon sequestering, which may also be of considerable significance to the climatic impact of atmospheric CO_2 enrichment, as the biological sequestering of carbon is a major factor in determining the CO_2 concentration of the atmosphere and the ultimate level to which it may rise.

APPROACH: In July 1987, eight 30-cm-tall sour orange tree (*Citrus aurantium* L.) seedlings were planted directly into the ground at Phoenix, Arizona. Four identically-vented, open-top, clear-plastic-wall chambers were then constructed around the young trees, which were grouped in pairs. CO_2 enrichment -- to 300 ppm above ambient -- was begun in November, 1987, to two of these chambers and has continued unabated since that time. Except for this differential CO_2 enrichment of the chamber air, all of the trees have been treated identically, being irrigated at periods deemed appropriate for normal growth and fertilized as per standard procedure for young citrus trees.

In April 1991, eight additional open-top chambers were constructed, into each of which were planted 12 new tree seedlings, including two different species of eucalyptus (*E. microtheca* and *E. polyanthemus*), the Australian bottle tree (*Brachychiton populneum*), and a conifer (*Pinus eldarica*). Two of these chambers have since been maintained at the ambient CO_2 concentration, two at 150 ppm above ambient, two at 300 ppm above ambient, and two at 450 ppm above ambient.

Numerous measurements of a number of different plant parameters have been made on the trees of both sets of chambers, some monthly, some bi-monthly, and some annually. Results of our findings are summarized below.

FINDINGS:

(1) Idso and Kimball (45)* conducted an inventory of the aboveground portions of the sour orange trees that had been exposed to ambient air and air enriched with an extra 300 ppm of CO_2 for a period of three years, finding the CO_2-enriched trees to have 100% more branches, 75% more leaves, and 190% more trunk, branch and fruit rind volume.

(2) Idso and Kimball (46)* measured the fine-root biomass in the upper 0.4m of the soil profile beneath the trees at 2-month intervals over the third year of the long-term sour orange tree study, finding the CO_2-enriched trees to have 2.3 times more biomass in this layer of soil.

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*For parenthetical references, see Appendix A, Manuscripts Published or Accepted in 1992.

(3) Idso and Kimball (44)* summarized four years of net photosynthesis measurements and two years of dark respiration measurements on the sour orange trees, finding the enhancement of the former and the reduction of the latter due to atmospheric CO_2 enrichment to be stable over time and to imply a 3.8-fold amplification of tree growth for a doubling of the current atmospheric CO_2 concentration and a 6.6-fold amplification for a tripling of the air's CO_2 content.

(4) Idso, Kimball and Hendrix (49)* measured a number of leaf parameters at 2-month intervals over a 2-year period, finding leaf dry weight of sour orange trees to be unaffected by atmospheric CO_2 enrichment at a mean air temperature of approximately 4°C. At a mean air temperature of 35°C, however, individual CO_2-enriched leaves weighed up to 40% more than their ambient-treatment counterparts.

(5) Gries, Idso and Kimball (32)* measured the concentrations of 7 macro-nutrients and 5 micro-nutrients in the leaves and roots of the sour orange trees at 2-month intervals for a period of one year, finding that atmospheric CO_2 enrichment had no major effect on nutrient concentrations in these adequately fertilized trees.

(6) Idso, Kimball, Akin and Kridler (48)* showed that for a given enhancement of the air's CO_2 content, plants whose stomatal conductances are most reduced experience the greatest increase in foliage temperature. They also showed that sour orange tree leaves are not very responsive in this regard, and that when leaf chlorophyll contents are reduced under such circumstances, leaf temperatures may actually decline.

(7) Graybill and Idso (31)* analyzed tree-ring records in high elevation subalpine conifers at a number of locations scattered across the southwestern United States, finding a mean growth increase of 60% or more over the past two centuries. Based upon the increase in the air's CO_2 content over that same period, this is exactly the magnitude of growth stimulation that would be expected if the conifers responded to atmospheric CO_2 enrichment as do sour orange trees.

(8) Idso and Kimball (46)* measured the photosynthetic and dark respiratory responses of three Australian tree species to atmospheric CO_2 enrichment, finding them to be comparable to the corresponding responses of sour orange trees.

(9) Idso (40)* summarized many of the preceding findings in a review paper prepared for inclusion in the proceedings of an international conference in carbon dynamics and modelling.

(10) Idso (42)* described how the great response of woody plants to atmospheric CO_2 enrichment may be producing an expansion of shrubland in the American southwest.

(11) Idso (37)* described how this phenomenon may be altering (greening) the face of the entire biosphere.

INTERPRETATION: The implications of our findings have a direct bearing on the current debate over anthropogenic CO_2 emissions. They clearly demonstrate that CO_2 is not a pollutant, but that it is instead a very effective aerial fertilizer.

FUTURE PLANS: We anticipate continuing the sour orange tree experiment for several more years, focusing on the effects of atmospheric CO_2 enrichment on fruit production. We also plan to study CO_2 effects on eldarica pine trees.

COOPERATORS: Institute for Biospheric Research; U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research.

ESTIMATING THE FRACTION OF ABSORBED PAR IN ALFALFA WITH REMOTELY SENSED PARAMETERS

Paul J. Pinter, Jr., Research Biologist

PROBLEM: A growing number of reports have established that the fraction of photosynthetically active radiation absorbed by a plant canopy (fA_{PAR}) can be reliably estimated from multispectral reflectance measurements. This approach is cost-effective and adaptable to remote sensing on all scales. It is also widely acknowledged that single waveband reflectance factors, vegetation indices (VIs), and fA_{PAR} vary as a function of plant growth and development (viz. leaf area, canopy architecture, cover, and phenology). Since they also change with sensor viewing angle and direction of incident solar energy, it is important to test whether the predictive relationships between fA_{PAR} and canopy reflectance parameters (especially VIs) are independent of significant bidirectional effects. Experimental verification of this hypothesis would extend the usefulness of remote sensing techniques for monitoring diurnal, seasonal, and latitudinal trends in fA_{PAR}.

APPROACH: Experiments were conducted on alfalfa (*Medicago sativa* L.) at The University of Arizona's Maricopa Agricultural Center near Phoenix, Arizona, during the MAC-VI investigations of bidirectional reflectance from agricultural targets. Three alfalfa fields with canopies of varying age and biomass and one mostly bare soil plot with a small amount of decaying alfalfa litter were selected for measurements. Above-ground biomass was determined at the conclusion of the experiment on the second day from 6 circular (0.5 m^2) samples taken at random from each alfalfa field, separated into brown and green components, and dried to a constant weight in a 55 °C oven.

A hand-held, line quantum sensor (LI-191, LiCor, Inc.) was used to estimate fA_{PAR} in 6 different locations within each target using the light balance approach of Gallo and Daughtry (1985). This sensor measures incident hemispheric light in the PAR (0.4 to 0.7μm) region of the spectrum. Twenty-four measurements of red (0.61-0.68 μm) and near-infrared (NIR, 0.79 to 0.89 μm) reflectance were obtained from the same canopy, using a hand-held, nadir-viewing radiometer (Model 100BX, Exotech, Inc.) with 15° fov optics. Data-reduction techniques were similar to those outlined by Pinter and Jackson (1985). Observations were made at approximately hourly intervals on two successive mornings (September 7-8, 1991). Solar zenith angles varied from less than 30° to more than 70° during the experiments. High resolution spectral observations were also obtained with a Personal Spectrometer II (Analytical Spectral Devices, Inc.). This spectroradiometer has ~4 nm spectral resolution over a nominal 350 to 1050 nm range. Measurements were made over the same alfalfa and soil targets with the instrument pointed nadir and fitted with the 15° fov restricting foreoptics. Target radiances were ratioed against irradiances estimated from a painted, calibrated $BaSO_4$ standard to obtain reflectance factors in each wavelength interval.

FINDINGS: Canopy reflectance and fA_{PAR} parameters were strongly influenced by solar zenith angles. Figure 1 illustrates this with a commonly used vegetation index, the normalized difference [NDVI = (NIR-Red)/(NIR+Red)], and fA_{PAR} data measured in all targets on both days. Each alfalfa canopy showed considerable variation in NDVI and fA_{PAR} as a function of solar zenith angle (Fig. 1a-c). Both responded as expected to changes in illumination angles over the 5-hour measurement periods. Maxima occurred at large solar zeniths, when direct beam sunlight entered the canopy obliquely and had the highest probability of interacting with foliage elements. Minima were attained near solar noon, when light had the shortest path length through the canopy. The largest dynamic range of NDVI and fA_{PAR} was observed in the relatively short alfalfa regrowth stubble (Fig. 1a), where values at solar zeniths near midday were only half those observed earlier in the morning.

The NIR, ratio vegetation index (Ratio = NIR/Red) and soil adjusted vegetation index [SAVI = (NIR-Red)/(NIR+Red+0.5)*1.5] behaved in a manner similar to the ND (these reflectance parameters are not shown in the figure). Red reflectance displayed an inverse relation with solar zenith, with maximum values occurring at smallest solar zeniths (also not shown). Behavior of NDVI and fA_{PAR} in the soil target was quite different (Fig. 1d). The slight systematic decrease in soil NDVI towards midday was caused by a gradual drying of the surface and reduction in surface shading by microtopography and decaying litter. The relatively small deviations of soil fA_{PAR} from expected values of zero were attributed to low light intensities and experimental difficulties in leveling the line quantum sensor. The high resolution spectral data from the Personal Spectrometer II have not yet been analyzed.

Simple correlation coefficients between fA_{PAR} and the various canopy reflectance indices were computed for each alfalfa targets individually and also for the alfalfa targets combined with data from the soil (Table 1). All correlations, except those for NIR in the regrowth alfalfa stubble were statistically significant. Although there is not an exact one-to-one correspondence, preliminary conclusions suggest that the relationship between commonly used (nadir) vegetation indices and fA_{PAR} were largely independent of solar zenith angle (i.e. time of measurement).

INTERPRETATION: Results establish NDVI as a reliable surrogate for estimating the amount of solar energy captured by an alfalfa canopy and available for use in photosynthetic pathways. Perhaps more importantly, however, these non-invasive procedures will spawn insight into the interactions between solar energy and the light-capturing apparatus of plants, which changes dynamically as a result of heliotropism and water stress. Quantitative estimates of fA_{PAR} are useful for validating models of plant growth and development and evaluating the effect of changing microenvironmental conditions and water stress on canopy light-use efficiency.

FUTURE PLANS: Research on appropriate methods and conditions for estimating fA_{PAR} in other crops, such as wheat, will continue. Similar techniques will examine the effect of solar zenith angle on the relationship between multispectral VIs and fA_{PAR} in wheat. This will provide a mechanism for evaluating the effect of CO_2 on light use efficiency of wheat in the 1992-1993 Free-Air CO_2 Enrichment (FACE) experiment at the Maricopa Agricultural Center.

The author wishes to thank Dr. Don Wanjura, USDA/ARS Plant Stress Laboratory, Lubbock, Texas, for the loan of the Line Quantum Sensor and Mr. Ric Rokey, Biological Technician, USDA/ARS U.S.Water Conservation Laboratory, for processing the plant samples.

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Table 1. Pearson product-moment correlation coefficients between fA_{PAR} and canopy reflectance parameters indicated in first column. The soil target is not shown separately because fA_{PAR} should always be zero. However, the soil target is included in the column titled "All targets combined."

	Regrowth Stubble (n=9)	Lush New Growth (n=9)	Mature Canopy (n=9)	All Targets Combined (n=36)
Red (0.61-0.68μm)	-0.960***	-0.833**	-0.887**	-0.946***
NIR (0.79-0.89μm)	+0.658NS	+0.827**	+0.731*	+0.702***
Ratio VI	+0.987***	+0.905***	+0.908***	+0.931***
NDVI	+0.977***	+0.916***	+0.920**	+0.982***
SAVI	+0.979***	+0.904***	+0.835**	0.963***

Significance levels: NS = p>0.05; * = p>0.01, ** = p>0.001, *** = p<0.001.

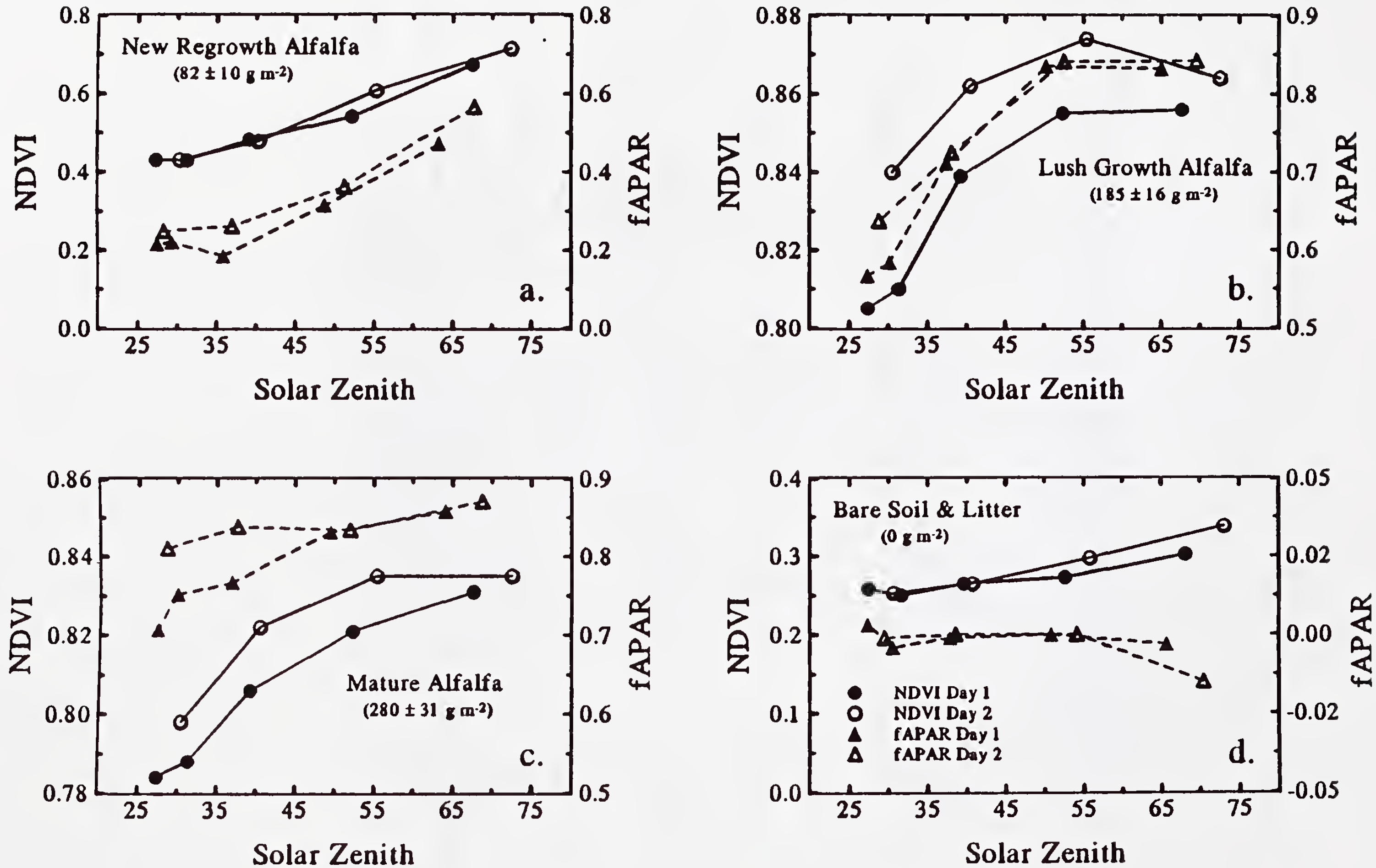

Figure 1. Normalized difference vegetation index (NDVI, solid lines) and fraction of absorbed photosynthetically active radiation (fA_{PAR}, dashed lines) versus solar zenith angle on 7-8 September 1991. Data are shown for a soil target and three alfalfa canopies at different stages of regrowth following harvest. The vertical scale in each figure is different. Legend for all figures appears in Fig. 1 d.

COMBINING REMOTE SENSING AND MODELING FOR ESTIMATING SURFACE EVAPORATION AND BIOMASS PRODUCTION

M.S. Moran, Physical Scientist; and
S.A. Maas, Plant Physiologist, ARS, Weslaco, Texas

PROBLEM: Remote sensing can be an effective means of estimating evapotranspiration and plant canopy density over a geographical region. While satellite-based sensors can easily be used to survey large areas on the earth's surface, a drawback to their use in operational monitoring programs is the relative infrequency of their observations of a given location, as a result of their overpass schedule and the occurrence of cloud cover. Thus, satellite-based observations represent *discrete* time events which may indicate little about how the biosystem got to its observed state or what its condition will be in the future. Numerous simulation models of the vegetation-soil-atmosphere system have been developed to provide *continuous* descriptions of vegetation growth and evapotranspiration. To be consistently accurate, these models generally require an extensive database of site-specific meteorological and edaphic information. The difficulty and expense of collecting this information on a regional scale often make the use of simulation models impractical for regional monitoring.

APPROACH: A possible solution to the operational monitoring problem is to use a simpler model which requires less ground information, and to supplement the model with periodic remotely-sensed estimates of surface evaporation and plant biomass. A simple model was designed to simulate both the evapotranspiration and biomass production of a vegetated surface, using infrequent remotely-sensed information and readily available meteorological observations (Maas et al., 1992). The model consists of two submodels--a soil-water balance submodel and a vegetation growth submodel. These submodels operate in sequence to produce simulations of evapotranspiration, soil moisture, leaf canopy density, and biomass production. A numerical procedure, called "within-season calibration", is used in the model to manipulate the values of certain parameters and initial conditions, so that model simulations are brought into agreement with remotely-sensed observations.

By its nature, this model is dependent upon development of accurate methods for estimation of some surface properties, using remotely-sensed spectral data (Moran et al., 1992). Physically-based and empirical relations were derived between spectral measurements and the model inputs (leaf area index (LAI) and daily surface evaporation) for an alfalfa stand in Phoenix, Arizona. Building on work by Jackson et al. (1977), a relation between daily evaporation (ET) and remotely sensed inputs was derived where

$$ET = A + B(T_s\text{-}T_a)/r_{ah}, \tag{1}$$

and A and B are empirical coefficients, and $(T_s\text{-}T_a)$ is the surface - air temperature difference. The resistance to sensible heat transfer (r_{ah}) was estimated by an empirically-derived exponential equation linked to SR, where

$$r_{ah} = e^{(4.62\text{-}0.091SR)}, \tag{2}$$

with r^2 value of 0.86.

FINDINGS: Based on field observations and remotely-sensed estimates of model inputs for an alfalfa field in Phoenix, Arizona, a preliminary test of the model was conducted to verify that it was performing in a reasonable manner.

Remotely Sensed Estimates of LAI and Daily Evaporation: For one alfalfa harvest cycle, the measured LAI data showed a curvilinear trend with the simple ratio (SR) of near-infrared and red reflectance. The relation between SR and LAI was significant, the mean absolute difference (MAD) between observed and predicted values of LAI was 0.6 (Fig. 1).

Using Eq. (2) and the remotely sensed measurements of T_s, T_a, and SR for alfalfa, the empirical parameters A and B of Eq. (1) were evaluated (Fig. 2). There was still a great deal of scatter about the regression line and the mean absolute difference (MAD) between predicted ET (using Eqs. (6) and (11)) and observed ET was 1.9 mm/day (Fig. 9b).

Preliminary Test of the Model: In the first test of the model, field observations of LAI and ET (rather than remotely-sensed observations), were used to calibrate the model, to insure that any differences between modeled

and observed conditions were not due to inaccuracies in estimating LAI and ET from remotely-sensed data. Results from the vegetation growth submodel are presented in Figure 3a. The LAI simulation fit the corresponding observations reasonably well, except that there was a tendency for the submodel to overestimate LAI early in the test period. The change in slope of the LAI simulation at Day 174 coincided with the observed onset of flowering in the crop. Simulated biomass increased over the duration of the test period and was in reasonable agreement with the observations, except for the tendency for the submodel to overestimate biomass early in the test period. Results from the soil-water balance submodel are presented in Figure 3b. The general trend in daily ET over the test period was simulated well. The increase in daily ET before Day 168 resulted from the increase in the vegetation canopy over this period.

The final step in this analysis was a test of the vegetation growth submodel and the soil-water balance submodel using periodic remotely-sensed estimates of LAI and ET for model calibration. The LAI simulation, based on remotely-sensed estimates (Fig. 4a), differed slightly from the simulation based on field observations (Fig. 3a). However, in both cases, the simulated values corresponded well with field observations. In general, daily ET values simulated with the model and periodic remotely-sensed estimates of ET corresponded well with field observations (Fig. 4b). In this preliminary test (Fig. 4b), the errors in daily ET were largest for the 10-day period from Day 159 to Day 169 during which there were no remotely-sensed data. Based on limited remotely-sensed data, the model resulted in a MAD of simulated and observed values of 1.61 mm/day over a range of ET values from 1 to 12 mm/day. This MAD was lower than the MAD computed for the estimation of ET using only the remotely-sensed data (where MAD = 1.9 mm/day).

INTERPRETATION: The empirical and semi-empirical relations derived for estimation of plant LAI and daily ET from remotely-sensed surface reflectance factors and temperature were sufficiently accurate for testing this combined modeling/remote sensing approach. However, application of these relations at local and regional scales is limited because of the site- and crop-specific nature of the derived relations. Future work towards an operational regional approach should address a more physically-based strategy.

The model formulation appeared to be adequate for simulating the evapotranspiration and biomass growth in this test involving alfalfa grown in an arid environment. We anticipate the best performance from this type of model in arid and semi-arid climates, where the evaporative demand of the atmosphere is large, rainfall events are infrequent and the soil surface is usually dry. A second test of the model is currently being conducted for the Walnut Gulch semi-arid rangeland watershed in southeastern Arizona.

FUTURE PLANS: Additional tests must be performed to evaluate the performance of the model under different soil water and vegetation-cover conditions. The effect of the frequency of remotely-sensed LAI and ET data on model accuracy must also be investigated. Since the meteorological and remotely-sensed information used in the model has spatial quality, the model could easily be incorporated into a Geographical Information System (GIS) to facilitate regional resource monitoring, assessment, and forecasting.

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Maas, S.J., M.S. Moran and R.D. Jackson (1992) Combining remote sensing and modeling for regional resource monitoring, Part II: A simple model for estimating surface evaporation and biomass production, Proc. ASPRS/ACSM/RT92, Wash. DC., 3-7 Aug. 1992, pp. 225-234.

Moran, M.S., S.J. Maas and R.D. Jackson (1992) Combining remote sensing and modeling for regional resource monitoring, Part II: A simple model for estimating surface evaporation and biomass production, Proc. ASPRS/ACSM/RT92, Wash. DC., 3-7 Aug. 1992, pp. 215-224.

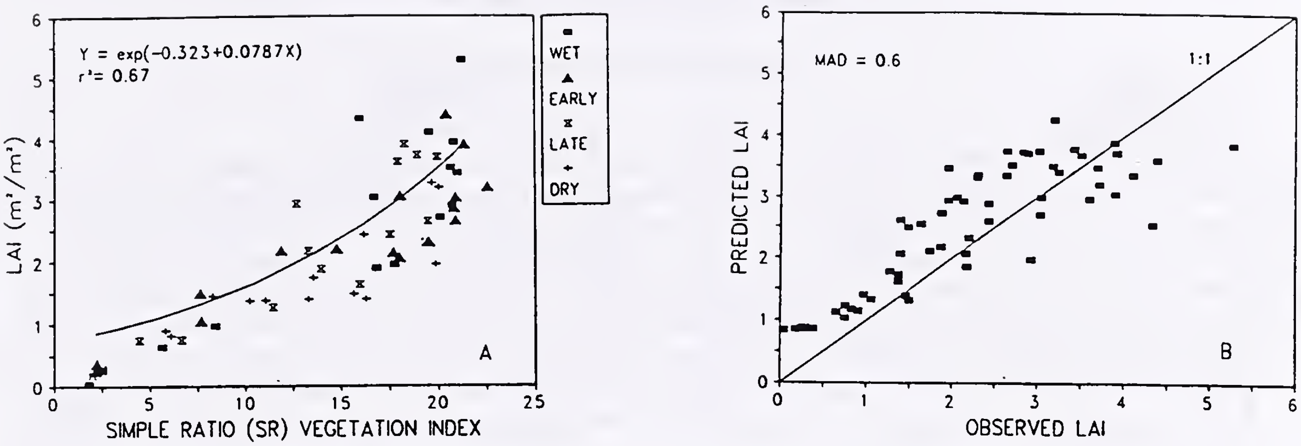

Figure 1. A) Empirical relation between alfalfa leaf area index (LAI) and SR vegetation index for four irrigation treatments ranging from WET to DRY. B) Comparison of observed LAI values with LAI predicted using the relation presented in A). MAD is the mean absolute difference between the observed and predicted values.

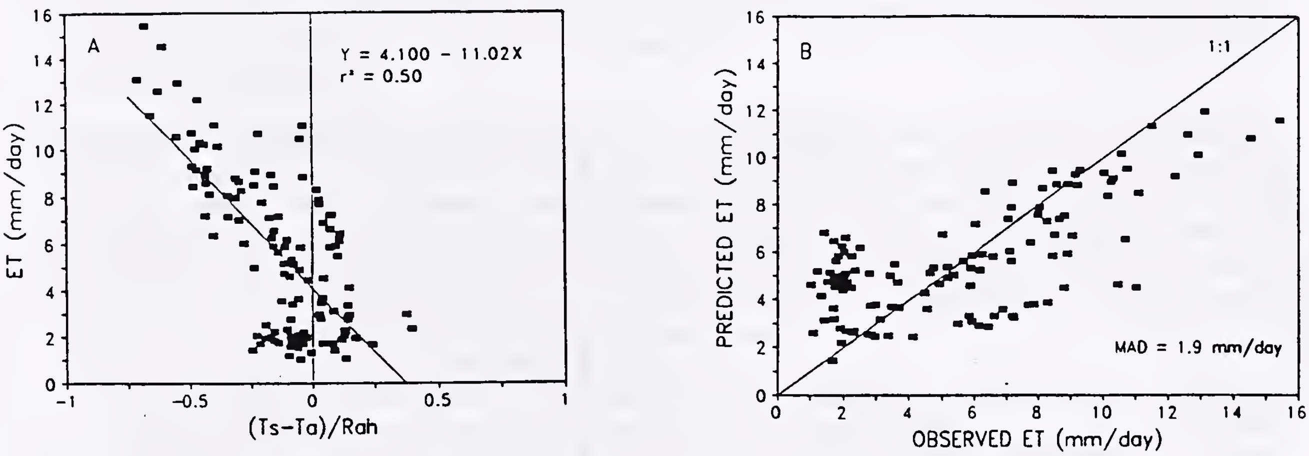

Figure 2. A) Empirical relation between observed daily surface evaporation (ET) from three lysimeters and surface-air temperature (T_s-T_a) divided by the resistance to heat transfer (r_{ah}) for irrigated alfalfa. The r_{ah} values were estimated based on the simple ratio (SR) vegetation inde^ and Eq. (8). B) Comparison of measured daily evaporation values (ET) with ET values predicted using Eqs. (6) and (8) and measurements surface and air temperature and surface reflectance. MAD is the mean absolute difference between the observed and predicted values.

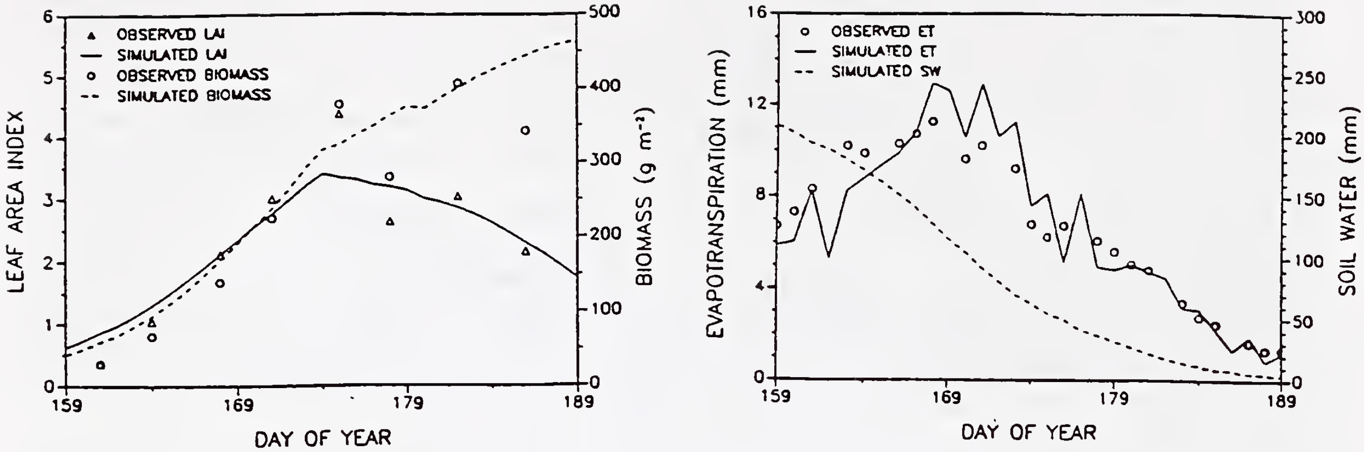

Figure 3. Preliminary test of the A) vegetation growth submodel and B) soil-water balance submodel based on periodic field observations of alfalfa canopy leaf area index, and daily evapotranspiration, respectively.

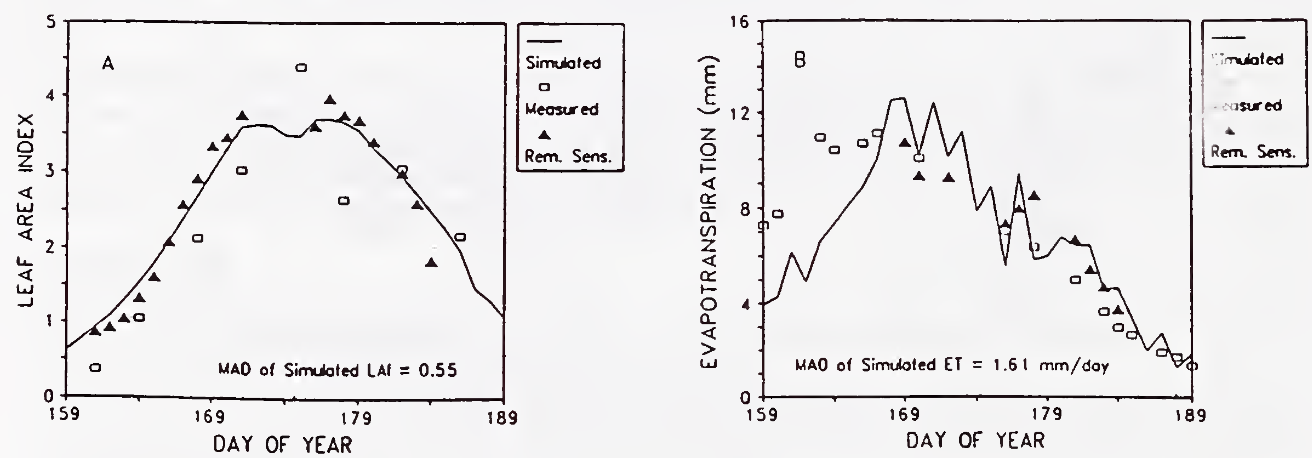

Figure 4. Simulated A) canopy leaf area index and B) daily evapotranspiration (B) based on periodic remotely-sensed estimates of LAI and ET, respectively. Field observations of LAI and ET were included for comparison with simulated and remotely-sensed estimates. MAD is the mean absolute difference between the observed and simulated values.

OPTICAL-MICROWAVE REMOTE SENSING FOR EVALUATION OF ENERGY AND WATER FLUXES

M.S. Moran, Physical Scientist

PROBLEM: Estimation of the energy and water fluxes of vegetated surfaces is of great interest for agriculture, hydrology, and climatology. Surface-energy transfer models provide a means of estimating surface flux based on vegetation and soil information, such as plant density, structure, and soil moisture. However, the detailed site information required as input to these models is generally not known; it is impractical to measure these inputs at regional scales using conventional techniques. On the other hand, it may be possible to use optical (visible to thermal infrared spectrum) and microwave remote sensing data obtained from satellite-based sensors to provide simultaneous vegetation and soil information for input to the model. Verification of this hypothesis is difficult, because it requires simultaneous optical and microwave data and ground-based meteorological data for several sites under a variety of atmospheric, edaphic and agronomic conditions.

APPROACH: An experiment was conducted to investigate the use of satellite-based optical and microwave data in combination with physical models for characterization of land surface and hydrologic properties of USDA-ARS Walnut Gulch watershed in southeastern Arizona during the dry and monsoon (wet) seasons (Moran et al., 1993). Nine Landsat TM scenes, three SPOT HRV scenes, and six ERS-1 synthetic-aperture radar (SAR) images were acquired to monitor the seasonal surface changes associated with the dry, early-monsoon, mid-monsoon, post-monsoon and "drying" seasons**. A team of scientists cooperated to make intensive surface measurements of vegetation, soil, and meteorological properties throughout the year and to be on-site during each satellite overpass to monitor atmospheric conditions and measure surface spectral and hydrologic properties (Table 1). The specific project goals for the semi-arid rangeland study were: 1) to investigate the use of optical and microwave data for characterization of hydrological parameters, such as soil moisture, surface runoff patterns, and vegetation cover and density; 2) to produce and verify maps of surface albedo and evapotranspiration, based on a synergism of optical and microwave data; and 3) to develop and refine methods for integration of optical and microwave data into hydrologic and erosion models.

FINDINGS: Considering that the experiment was only recently completed November 17, 1992, it is premature to present any conclusive results. Based on preliminary examination of the seasonal trends in the optical data (Fig. 1 and 2), it appears that the 8-month experiment succeeded in covering a wide range of vegetation cover and soil moisture conditions. The peaks and dips in the simple ratio (SR) of NIR and red reflectance correspond to variations in vegetation associated with the warm, rainy seasons in the spring and late summer, the dry, hot summer, and the dry, cool conditions in late fall. Variations in surface-air temperature (T_s-T_a) correspond to variations in both plant cover and surface soil-moisture conditions.

Preliminary analysis of the microwave data showed that

1) Both microwave backscatter and surface reflectance factors (red and near-IR) were correlated with rangeland vegetation cover and biomass, despite characteristically sparse vegetation cover;
2) SAR backscatter had a positive relation with soil moisture (0-5 cm depth) over a wide range of soil moisture contents, but this relation was weakest for discrimination of relatively dry soils; and
3) Synergism of low-resolution SAR data with high-resolution thermal measurements (from a low-altitude aircraft-based imaging system) improved estimates of soil heat flux and sensible heat flux densities.

** This research was made possible by the cooperative spirit of Steve Land of EOSAT Corp. and Guy Duchossois of the European Space Agency who provided Landsat TM and ERS-1 SAR images at no cost. Support was also provided by the NASA Interdisciplinary Research Program in Earth Sciences (NASA Ref. Num. IDP-88-086), the NASA Eos Program (NASA Ref. Num. NAG-W2425) and NSF (BSC-8920851).

INTERPRETATION: These results, in combination with the ease of registration of Landsat TM, SPOT HRV, and ERS-1 SAR images, imply potential for combination of these data in a Geographic Information System (GIS) for investigations of the extent and uniformity of hydrologic properties at regional scales.

FUTURE PLANS: The cooperating investigators in this experiment propose to utilize this data set to:

- Investigate applications of energy balance models to the riparian biome in the San Pedro Watershed
- Investigate the synergy of optical, thermal and microwave data for estimation of surface hydrologic parameters and evaluation of surface evapotranspiration
- Investigate variability relationships with increasing scale through the use of yoke-, aircraft- and satellite-based spectral data and degraded satellite-based images
- Evaluate a simple simulation model (supplemented with periodic remotely sensed data) for evaluation of daily evaporation and biomass production at watershed and regional scales
- Analyze the use of Ft. Huachuca radiosonde data with radiative transfer models for retrieval surface temperatures from satellite-based sensors
- Search for a simple, operational atmospheric correction techniques for retrieval of surface reflectance factors from satellite-based digital images
- Analyze the effects of solar and viewing angles on surface reflectance and temperature measurements based on low-altitude off-nadir and SPOT HRV off-nadir spectral data acquired in Walnut Gulch on two consecutive days
- Investigate the possibility of discriminating vegetation and soil temperatures (for energy balance evaluation) from composite temperatures measured at high-resolution over sparse vegetation
- Produce maps of hydrologic parameters, such as vegetation cover and density, soil moisture and daily evaporation, using optical and thermal images over Walnut Gulch and Niger for input into a GIS for storm-event and interstorm models
- Combine the low-resolution microwave (ERS-1) and the high-resolution thermal data (airborne thermal imager) to enhance the application of two-layer models for estimation of surface energy fluxes

COOPERATORS: M.A. Weltz[2], A. Vidal[3], D.C. Goodrich[2], S.A. Amer[4], D.S. Ammon[5], K. Batchily[6], J. Blanford[4], T.R. Clarke[1], L. Eastman[1], D. Fox[7], D. Gellman[8], M. Hodshon-Yates[4], H. Hendy[6], A.R. Huete[6], T. Keefer[2], K. Kiesel[4], L. Lane[2], A.F. Rahman[6], S. Sorooshian[4], D. Troufleau[3], C. Unkrich[2], J. Washburn[4]

[1] USDA-ARS U.S. Water Conservation Laboratory, 4331 E. Broadway, Phoenix, AZ 85044
[2] USDA-ARS Southwest Watershed Research Center, 2000 E. Allen, Tucson, AZ 85719
[3] CEMAGREF-ENGREF Remote Sensing Laboratory, B.P. 5095, 34033 Montpellier France
[4] The University of Arizona, Dept. of Hydrology and Water Resources, Tucson, AZ 85719
[5] Aerial Images, Division of Stanton Systems, Inc., 4240 E. Lee #11, Tucson, AZ 85712-3990
[6] The University of Arizona, Dept. of Soil and Water Science, Tucson, AZ 85719
[7] Soil Conservation Service, 201 E. Indianola Ave., Ste. 200, Phoenix, AZ 85012
Currently stationed at USDA-ARS SWRC, Tucson, AZ 85719
[8] The University of Arizona, Optical Science Center, Tucson, AZ 85719

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Moran, M.S., M.A. Weltz, A. Vidal, D.C. Goodrich, S.A. Amer, D.S. Ammon, K. Batchily, J. Blanford, T.R. Clarke, L. Eastman, D. Fox, D. Gellman, M. Hodshon-Yates, H. Hendy, A.R. Huete, T. Keefer, K. Kiesel, L. Lane, A.F. Rahman, S. Sorooshian, D. Troufleau, J. Washburn (1993) Characterization of hydrologic properties of semi-arid rangeland ecosystem from combined optical-microwave remote sensing, IEEE Symp. on Combined optical-microwave Earth and Atmosphere Sensing, 22-25 March 1993, Albuquerque, NM, (accepted).

Table 1. Summary of data acquisition and on-site field measurements, where DOY=day of year, TM=Landsat Thematic Mapper, SPOT=SPOT High Resolution Visible (HRV), ERS-1=ERS-1 Synthetic Aperture Radar, OD=atmospheric optical depth, RP=radiosonde atmospheric temperature and water vapor profile, VS=vegetation cover, biomass and LAI measurements at 2-6 sites, SM=soil moisture at 4 sites, STR=measurements of surface temperature and reflectance with ground-based and airborne radiometers throughout the watershed. In addition to these image acquisitions and field measurements, surface energy flux and basic meteorological information were measured on a half-hourly basis throughout the season. A network of rain gauges and automated flumes was monitored to determine the spatial distribution of rainfall and runoff.

Date	DOY	Weather	TM	SPOT	ERS-1	VS	OD	RP	SM	STR
23 Apr.	114	Marginal	yes		25 Apr.	21-23 April	yes	yes	yes	Ground-based
9 May	130	Clear	yes		14 May		yes	yes	yes	Ground-based
25 May	146	Cloudy	no			27-28 May	no	yes	yes	Ground-based
10 June	162	Clear	yes		18 June		yes	yes	yes	Ground-based
26 June	178	Clear	yes			22-23 June	no	yes	yes	Ground-based
12 July	194	Good	yes			14-15,17 July	yes	no	no	Ground-based
28 July	210	Cloudy	no			28 July	no	yes	yes	Ground & Aircraft
11 Aug.	224	Clear		yes		11-12 August	yes	no	no	Ground-based
13 Aug.	226	Marginal	yes			13 August	yes	yes	yes	Ground-based
29 Aug.	242	Cloudy	no		27 Aug.		no	yes	no	
6 Sept.	250	Clear		yes			yes	no	no	Ground & Aircraft
7 Sept.	251	Clear		yes			yes	no	no	Ground & Aircraft
14 Sept.	258	Cloudy	no			15-16 Sept.	no	no	yes	Aircraft-based
30 Sept.	274	Clear	yes		1 Oct.	30 Sept.	yes	yes	yes	Ground & Aircraft
16 Oct.	290	Clear	yes		17 Oct.	16-17 Oct.	yes	yes	yes	Ground & Aircraft
1 Nov.	306	Clear	yes		5 Nov.		yes	yes	yes	Ground & Aircraft
17 Nov.	322	Clear	yes			18-20 Nov.	yes	yes	yes	Ground & Aircraft

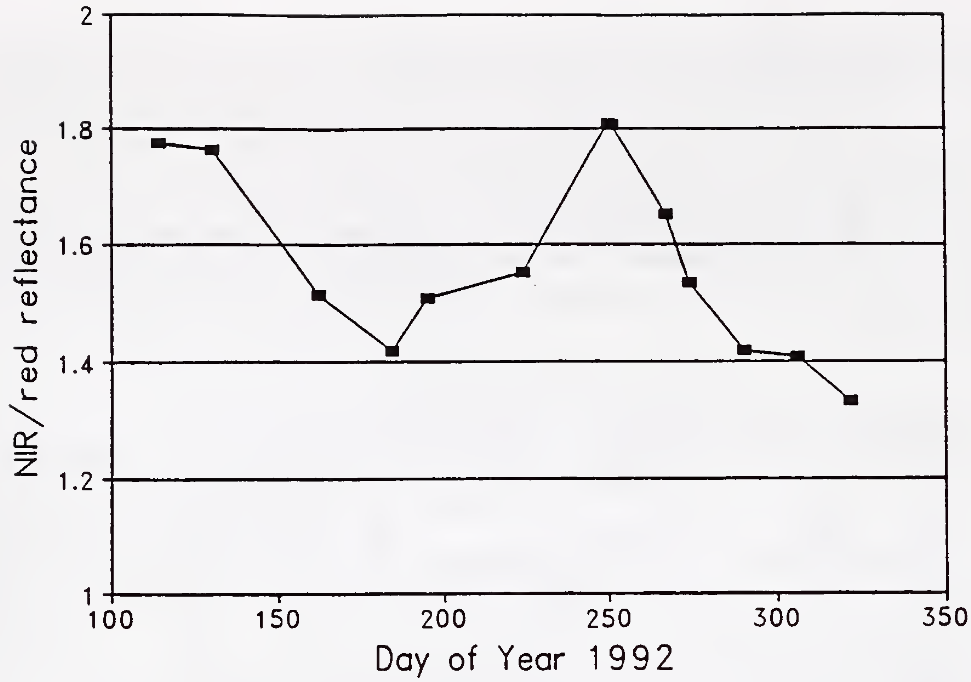

Figure 1. Seasonal trends of the simple ratio (SR) of NIR and red reflectance at the grass-dominated Kendall site at Walnut Gulch Experimental Watershed.

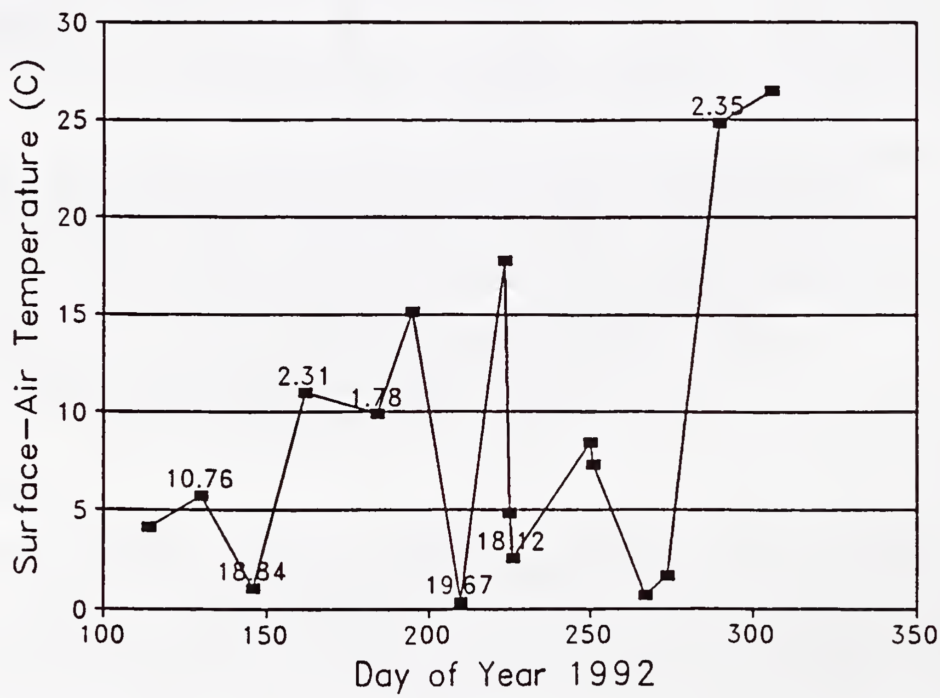

Figure 2. Seasonal trends of the surface-air (T_s-T_a) temperatures (C) at the grass-dominated Kendall site at Walnut Gulch Experimental Watershed. Volumetric soil moisture data (%) were listed with several data points.

1992 HAPEX-SAHEL EXPERIMENT: QUANTIFYING THE HYDROLOGIC CYCLE FOR ARID/SEMI-ARID REGIONS

M.S. Moran, Physical Scientist; and
T.R. Clarke, Physical Scientist

PROBLEM: The World Climate Research Program recommended a series of regional studies of surface atmosphere interactions. In response to this recommendation, five experiments have been completed or planned that fit the requirements set out by this body:

- HAPEX-Mobilhy (SW France 1986)	Temperate forest and cultivation
- FIFE (Kansas 1987-1989)	Tall-grass prairie
- EFEDA (La Mancha, Spain 1991)	Arid mediterranean
- HAPEX-II-Sahel (Niger 1992)	Sudanian-Sahelian steppe
- BOREAS (Canada 1993)	Boreal forest

This report addresses the USWCL participation in the HAPEX-Sahel Experiment, which was designed to study the surface energy and water balance at scales from 100 m^2 - 10000 km^2. The USWCL contribution to the HAPEX-Sahel Experiment was the study of the special problems associated with estimating components of energy balance over sparse canopies with remotely-sensed data. The overall research goal was to understand and quantify the water and energy balance of arid/semi-arid regions at various spatial scales with a combination of readily-available ground data and remotely-sensed data. The specific experimental goals were related to three task areas, with special emphasis on the technical challenges associated with sparse vegetation at increasing spatial scales:

1) Develop techniques to estimate components of the surface energy balance from a combination of optical and microwave remotely sensed data and ground-based estimates of air temperature and wind speed;
2) Develop techniques to estimate, from multi-temporal and multi-directional remotely-sensed data, some of the important surface characteristics which control surface fluxes of moisture and energy, such as vegetation density; and
3) Refine and validate a model that simulates transfer of mass and heat in the soil/plant/atmosphere continuum, utilizing the fluxes described in task (1) and land-surface characteristics derived from remotely-sensed data described in task (2).

APPROACH: In order to meet the above-mentioned research goals, the following measurements were made in fallow and grass- and shrub-dominated study sites in central Niger :

1) Ground-based and light aircraft-based measurements of visible and NIR reflectance and surface temperature along linear transects;
2) Ground-based measurements of multi-directional radiances in visible and NIR and spectral bands to investigate the coupled effects of soil background, view zenith and azimuth angles, and solar angle on surface reflectance, temperature and vegetation indices;
3) Measurements of surface for validation of simplified soil/plant/atmosphere simulation models;
4) High temporal resolution ground meteorological data (wet/dry bulb temperature, wind speed and solar radiation) to use in conjunction with remotely-sensed data for estimation of surface fluxes and validation of simulation models; and
5) Measurements of spatial variability of vegetation properties such as grass and shrub cover and biomass for studies of surface heterogeneity and scaling effects.

FINDINGS: Data reduction and analysis is still in a preliminary stage and it is too early to present any results.

FUTURE PLANS: Analysis of data will continue, including attempts to merge our research results with those of other HAPEX-Sahel cooperators studying similar topics at other sites. Synergism of optical and microwave data with flux models and Bowen ratio measurements will be made as these data become available.

COOPERATORS:

M. Weltz, D. Goodrich, USDA-ARS Southwest Watershed Research Center, Tucson, AZ
A. Huete, W. van Leehwan, The University of Arizona, Dept. of Soil and Water Science, Tucson, AZ
S. Sorooshian, The University of Arizona, Dept. of Hydrology and Water Resources, Tucson, AZ.z.
Y. Kerr, LERTS, Toulouse, France
A. Vidal, CEMAGREF-ENGREF Remote Sensing Laboratory, Montpellier, France
K. Humes, B. Kustas, USDA-ARS Hydrology Laboratory, Beltsville, MD
S. Prince, University of Maryland, College Park, MD

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Airborne Thermal Imagery as a Farm Management Tool

Thomas R. Clarke, Physical Scientist

PROBLEM: Subsurface drip irrigation, while showing great potential for reducing water use by crops, introduces a unique problem to irrigation managers. Traditional methods for measuring soil moisture, and hence the adequacy of irrigation rates, are no longer effective. Gravimetric or neutron probe measurements, necessarily made away from the drip emitter, can underestimate the soil moisture available at the plant's roots.

APPROACH: Leaf temperature has been found to be a good indicator of soil moisture in the root zone (Idso and Ehrler, 1976). Weekly overflights of a commercial melon farm were made, using a thermal scanner, from June to November. The instrument is sensitive to radiation in the 8-to 12-micron bandwidth, and has a 20-degree horizontal field of view. Most images were acquired from an altitude of 2300 meters, providing a spacial resolution of approximately 2.5 meters. Images were processed and presented to the farm manager within 24 hours of data acquisition.

FINDINGS: The images proved useful to the farm manager for comparing relative water stress of melon fields with full canopy cover. Irrigation practices were altered in at least one case as a result of the images. However, partial canopy cover allowed soil background temperatures to overwhelm the leaf temperature signal, making it impossible to differentiate between non-stressed partial canopy crops and water-stressed full canopy crops.

FUTURE PLANS: A complementary digital camera system, providing images in the red and near-infrared wavelengths, is being developed at this laboratory. Combining the resulting two images into a vegetation index and registering the result to a simultaneous thermal image, the relationship of temperature to the amount of vegetation can be studied, allowing the researcher to estimate or permitting the estimation of canopy temperature under less than full canopy conditions.

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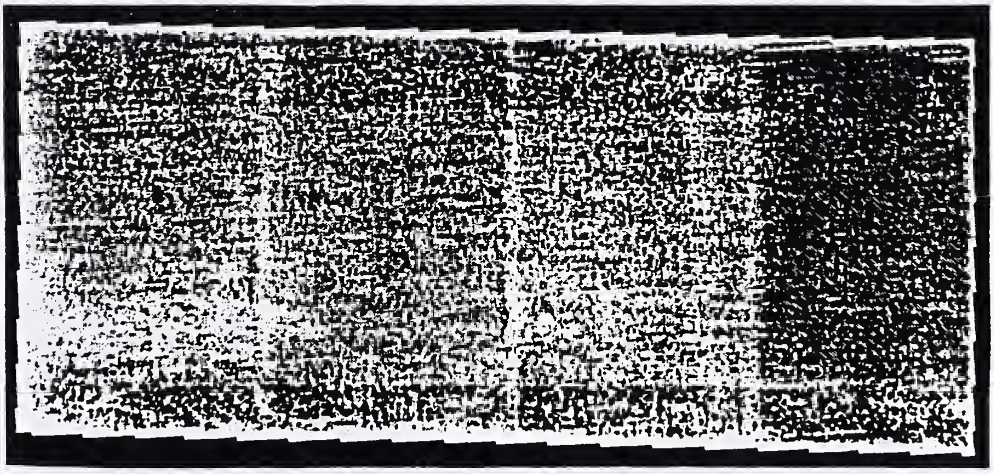

Figure 1: Thermal image of a sub-surface drip irrigated cantaloupe field June 11, 1992. The section to the extreme right received 50% more water than the other three sections, resulting in better growth and less exposed soil, thus, appearing cooler.

DEVELOPMENT OF A LOW COST MULTISPECTRAL IMAGING SYSTEM USING DIGITAL CAMERAS

Thomas R. Clarke, Physical Scientist

PROBLEM: High resolution imagery of agricultural targets from airborne sensors has received increased attention in recent years as a tool for farm management. Most imaging systems have been based on video cameras, with the data stored as analog signals on video tape. Aside from slow "shutter" speed, limited resolution, and possible loss of radiometric accuracy in the recording and play-back process, time and effort must be expended finding, extracting, and digitizing desired images for analysis. Since the images become less valuable to the farm manager with increasing delay, every effort should be made to shorten the processing time.

APPROACH: A recent development in the field of electronic imagery is the low-cost digital camera, used primarily for desk-top publishing. The device collects an image on a Charge Coupled Device (CCD) array, which is immediately converted to digital form and either sent to a computer for storage or stored on a chip within the camera itself. Since these cameras are mass-produced, the cost, even for customized versions, is quite low. No analog recording medium is used, and the resulting data consist of discrete images of the desired targets, rather than a moving target to be "grabbed" later.

Three Dycam Model 3 cameras were obtained with the following modifications provided by the manufacturer: the infrared blocking filter was omitted (extending the devices' spectral sensitivity to 1.2 microns) and the optics-to-electronics assembly was rearranged to allow the cameras to be mounted closer together, thereby minimizing parallax problems. The cameras have a 496 by 365 pixel CCD array, can be programmed for either automatic or fixed exposure times of 0.5 to 650 milliseconds, and can store 32 images internally on a memory chip. Interference filters were purchased separately, for a total cost per camera of approximately $1,500.

RESULTS: The camera system has been "flown" once with satisfactory results. A permanent housing is now being built to will allow the system to be mated to a thermal scanner, if desired, in order to capture images simultaneously in the green, red, near-infrared, and thermal bandwidths. Disadvantages of the low-cost digital cameras include the 32-image capacity, and the 5- to 7-second interval required between image acquisitions. Preliminary tests indicate an inherent dark current, even at very short exposure times. However, the system appears to be more than adequate for testing the usefulness of remotely sensed data, when processed in a timely manner, as a tool for farm managers.

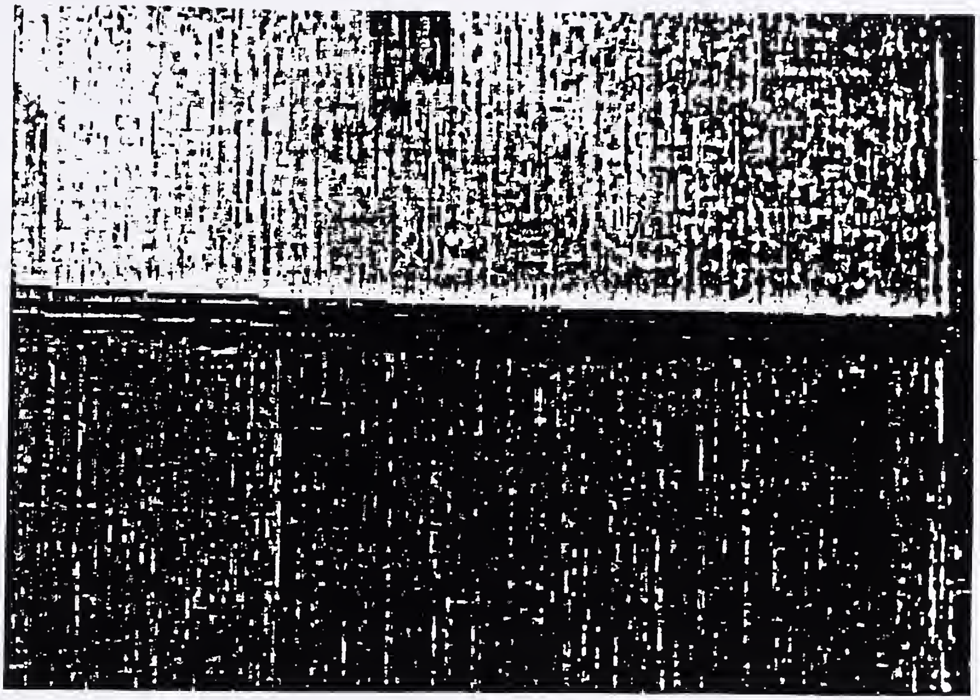

Figure 1. Soil Adjusted Vegetation Index (SAVI) of two lettuce fields using digital counts from Dycam 3 cameras with red (600-670 nm) and near-infrared (790-890 nm) interference filters. The bottom field has been harvested, and harvesting has just begun in the upper center and lower left of the upper field. Image brightness is proportional to vegetation index.

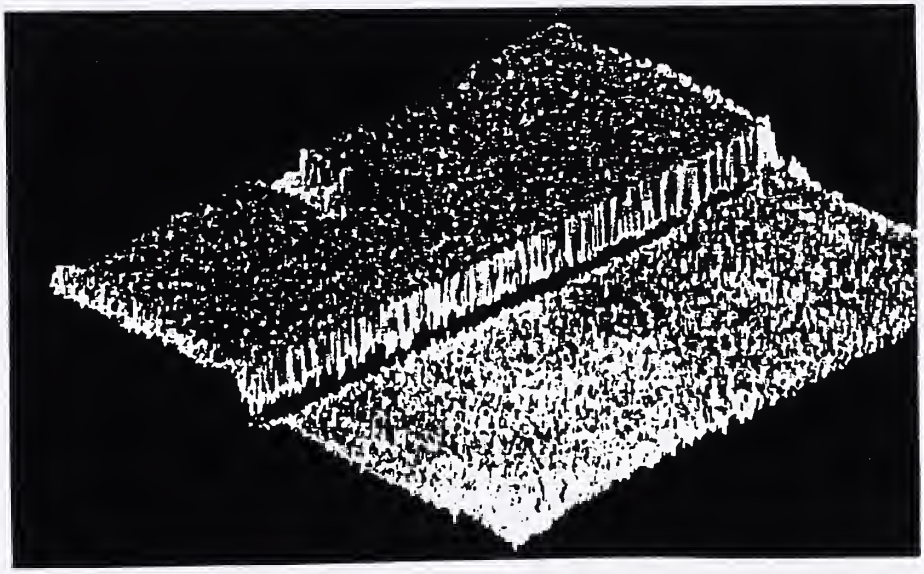

Figure 2. Terrain model of the above image, using SAVI as the vertical component and surface temperature as the gray scale. Image brightness is proportional to temperature.

GERMPLASM IMPROVEMENT AND CULTURAL DEVELOPMENT OF NEW INDUSTRIAL CROPS

EFFECTS OF STORAGE ON GUAYULE RUBBER CONTENT AND ANALYSIS

F.S. Nakayama, Research Chemist

PROBLEM: Guayule rubber degradation starts from the instant the shrub is harvested and continues to the time the prepared sample is analyzed. Degradation of field-stored guayule will decrease the amount of extractable rubber, whereas, degradation in laboratory-handled and stored samples may give misleading information about the rubber status of the shrub, be it freshly harvested or stored. The objectives of this study were to determine changes occurring in the rubber content of harvested guayule shrub and the effects of sample preparation and storage time on rubber analysis.

APPROACH: I. Harvesting and Storage

This experiment involved determining the effects of field storage time and bale size on the rubber content of baled guayule shrub. Mature shrubs were harvested and baled by Dr. Wayne Coates, University of Arizona, using equipment specially developed for the guayule plant. Eight plants per replicate, with two replicates per plant row, were sampled immediately after harvest for water, resin, and rubber content. Bales were made from the harvested shrubs at two-, four- and eight-day intervals after harvest. Two cylindrical bales, a large one with dimensions of 1.52 m width, x 1.83 m diameter, weighing 910 kg (5 ft width, x 6 ft diameter, 2000 lb) and a small bale at 1.22 m width, x 1.22 m diameter weighing 450 kg (4 ft width, x 4 ft diameter, 1100 lb) were used. The bales were stored in the field. All field samplings were conducted at Marana, Arizona.

After baling plant samples were taken at weekly intervals. The bales were cut into smaller sections with a gas-powered chain saw. At least eight plants were included per section per replicate, with two replicates per sampling for the various analyses. An initial rough chipping of the sections was made in the field with a chipper. The chipped materials were subsampled for water content, to follow the drying behavior of the baled materials. Another, finer, plant grinding was carried out at the laboratory the same, or the following day, with a garden-type shredder; the plant samples were immediately frozen in plastic bags. A final grinding was done on a grinding mill (2 mm) just prior to analysis. The chipped material was frozen in liquid nitrogen to help in the grinding process. All the preceding steps were carried out as rapidly as possible to minimize storage time and sample exposure.

II. Analysis and Antioxidants

Separate shrub materials were stored in the greenhouse, air-dried in the shade, or frozen. Later, ground materials were frozen, air-dried, and oven-dried. Stems of freshly harvested shrubs were treated with 0.1 and 1.0 percent antioxidants (AO) in the grinding step and analyzed after various storage periods. The AO's used were AgeRite (alkylated-arylated bisphenolic phosphite), Butyl Zimate (zinc dibutyl-dithiocarbamate), Santowhite (4,4'-thiobis(6-tert-butyl-m-cresol), and BHT (2,6-di-tert-butyl-4-methylphenol). The first three compounds are used in the natural rubber processing industry. BHT is regularly used in household products as a food preservative.

Gravimetric rubber and resin analyses were carried out using the homogenizer technique. Water content of the shrub was determined at 50 C drying temperature.

FINDINGS: I. Harvesting and Storage

The rubber and resin contents of the whole plant (Table 1) and stored bales (Table 2) did not decrease with time over the 0- to 32-day period. In fact, there was a tendency for the rubber content to increase with time. This was probably due to the loss of leaves as the plant dried out. Similarly, the rubber content of the baled material increased, but the increase was more dramatic for the first-day baled sample because of the large amount of leaf drop during the baling process (Table 2). This behavior was normal for all varieties and all harvest days. Relatively little change in resin content was observed over the storage period.

No significant difference in rubber-content behavior with time was observed between the large (910 kg) and the small (450 kg) bales. The temperatures inside the two bale sizes were similar and close to that of the air. Thus, there appears to be no danger of spontaneous combustion of guayule bales as opposed to the period with moist forage bales that are densely packed and poorly ventilated.

II. Analysis and Antioxidants

The results showing the interaction of sample preparation, storage time, and leaves are listed in Table 3. An interaction exists among these parameters, and possibly the leaves contribute most to the total degradation effect. As noted earlier in the baling description, the loss of leaves when the whole shrub is left in the field actually caused an increase in rubber content. Organic acids in the leaves could contribute to rubber degradation when the leaves and branches are ground together and stored.

Contrary to expectation, the rubber contents in the air-dried or oven-dried (50° C) samples were similar to the fresh plant materials. Analyses were corrected for moisture content. Drying, although exposing the cell rubber deposits to air and oxidation, may inhibit or deactivate the enzyme or associated process related to rubber degradation. In the case of the fresh frozen sample, degradation can occur when the material is thawed for sample preparation prior to rubber analysis. Presently, rubber content values reported in the literature are based on the analysis of either fresh, air-dried, and oven-dried preparations. Degradation of guayule rubber in shrubs noted in early reports may have been due to an actual rubber content change in field-stored shrubs, confounded by a decrease in rubber in the prepared round materials rom sample storage and handling, before rubber analysis.

Four types of antioxidants mixed with the stem materials during grinding were able to prevent a decrease in rubber content, even when the ground samples were exposed directly to the atmosphere (Table 4). Antioxidant additions of as little as 0.1% were able to control rubber degradation when pre-mixed with the ground material. In the solvent-extraction process for removing rubber from the shrub, antioxidants are added to the solvent system. Thus, part of the total AO added to the solvent could be redirected to the plant preparation step. The AO can be mixed with the shrub in the chopping and grinding step to prevent rubber degradation at an earlier stage in the processing of shrub. Usually, the ground shrub is temporarily stored before it is put through the extraction process.

INTERPRETATION: To avoid rubber degradation, the leaf should be separated from the harvested shrub. Careful handling of plant materials is important prior to rubber and resin analysis. Contrary to popular belief, the oven-dried plant material had rubber contents similar to air-dried or frozen samples. The rubber content of freshly ground shrub could be maintained by treatment with antioxidants for a period of at least one month. Laboratory sample preparation and laboratory storage conditions greatly affect the analytical results of resin and rubber determinations.

FUTURE PLANS: Analytical studies will continue on rubber and resin and on factors, such as leaves and antioxidants, that affect rubber and resin contents. Work will begin on determining the effect of sample treatment on rubber molecular weight.

Table 1. Effect of storage time on guayule rubber content of whole guayule shrubs.

Storage (day)	Rubber content, (%)
0	5.83 a*
2	5.82 a
4	6.63 a
9	6.45 a
16	7.30 a
32	7.03 a

* Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls test.

Table 2. Effect of storage time on guayule rubber and resin contents of baled guayule shrubs.

Storage (day)	Rubber content (%)	Resin content (%)
0	6.55 b*	7.14 ab
4	7.18 a	7.75 a
18	7.62 a	7.03 b
25	7.30 a	7.43 ab
32	7.62 a	7.27 ab

*Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls test. Lower case letters also indicate ranking.

Table 3. Effect of leaves, plant preparation, and storage time on guayule rubber content

Source	SS	df	MS	F	P
Main Effects					
TIME	18.0303	4	4.5076	38.8498	0.0000 ***
PREP	3.5776	3	1.1925	10.2780	0.0000 ***
LEAF	113.5858	1	113.5858	978.9721	0.0000 ***
Interaction					
TIMExPREP	2.2036	12	0.1836	1.5827	0.1055 ns
TIMExLEAF	0.9426	4	0.2356	2.0310	0.0943 ns
PREPxLEAF	1.1745	3	0.3915	3.3741	0.0207 *
TIMExPREP xLEAF	4.7046	12	0.3920	3.3790	0.0003 ***
Error	13.92307	120	0.1160		
Total	158.14202	159			

MULTIPLE RANGE TESTS

TIME

Time (day)	Mean (% rubber)
0	6.0 a
1	5.6 b
7	5.7 b
14	5.7 b
28	5.0 c

TREATMENT

Treatment	Mean (% rubber)
Air-dried	5.8 a
Oven-dried + air-dried	5.7 a
Oven-dried	5.5 b
Frozen	5.5 b

LEAVES

Leaves	Mean (% rubber)
No leaves	6.6 a
With leaves	4.8 b

Table 4. The effect of antioxidants on the rubber content of ground guayule shrub--four-week storage.

Treatment	Storage (day) 0	28
	----Rubber (%)----	
Check	6.68 a*	5.36 b
AgeRite, 0.1%	5.99 a	5.52 a
AgeRite, 1.0%	6.21 a	5.52 a
Butyl Zimate, 0.1%	5.32 a	5.26 a
Butyl Zimate, 1.0%	5.85 a	5.56 a
Santowhite, 0.1%	6.15 a	5.56 a
Santowhite, 1.0%	6.33 a	6.21 a
BHT, 0.1%	6.64 a	6.46 a
BHT, 1.0%	7.28 a	6.45 a

* Paired comparison between 0 and 28 days for each treatment. Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls test.

BREEDING IMPROVEMENTS OF GUAYULE GERMPLASM

D.A. Dierig, A.E. Thompson, Research Geneticists; and
F.S. Nakayama, Research Chemist

PROBLEM: Successful development and commercialization of guayule as a potential rubber crop depends on higher yielding germplasm. In addition to rubber, guayule produces significant amounts of resins and other potentially useful by-products that will also have a significant impact on successful commercialization. We have found extensive variation for characteristics of guayule that are related to rubber and resin yield, implying that simple selection would be possible. Apomixis (asexual reproduction by seed) then allows the plant to carry the trait to the subsequent generations. However, new generations do not always possess the desired characteristics. This is due in part to periodic sexual reproduction and environmental influences on genetic traits. The objective of our breeding program is to generate germplasm containing variability for traits that correlate to yield, and, once promising germplasm is identified, to develop breeding strategies that enable us to control that variation. The ultimate goal is to develop new germplasm and varieties with sufficient rubber and resin yields to fully commercialize production.

APPROACH:

1. The final accumulation of data was collected this year in a three-year study of 22 new breeding lines selected for yield and agronomic characteristics. Plants were harvested each year and evaluated for biomass, rubber and resin content, rubber yield, and regeneration following harvest by clipping. Rubber yields from the same plant, which was allowed to regenerate twice, were also evaluated to determine productivity under a multiple harvest system.
2. A study of variation in progeny descended from an apomictic parent, using the 22 breeding lines, is in progress. The parent and individual progeny were compared for yield and agronomic characteristics. Isozyme analyses which measure different forms of polypeptides in a plant protein were used as genetic markers. Isozymes have an advantage for use as markers because they are not influenced by environmental factors. These data allowed us to calculate an estimate of the genetic variance in the progeny and the heritability of the traits we selected for in guayule.
3. A total of 70 other breeding lines from single plant, apomictic, selections are being evaluated for improved rubber and resin content, yield, plant vigor, and regeneration ability.
4. A base, sexually reproducing diploid population has been established for recurrent selection. The plants, now two years old, will be analyzed and evaluated this year. Superior plants will be selected for the next round of recurrent selection.
5. Hybrid plants from sexual diploid-by-apomictic tetraploid crosses have been field planted. These hybrids possessed the apomictic characteristic, although they resulted from sexual recombination. This new methodology exploits the variability of the apomictic pollen plants, and new selections can be made from the resulting segregating population.
6. The feasibility of harvesting new, higher yielding selections at an earlier age is being examined as a means of increasing rubber yield on a per area basis. Three new breeding lines and a check variety were planted at three different plant spacings and yields will be compared. The experiment is also designed to determine how many successive harvest cycles can be made from clipping on a two-year cycle.

FINDINGS: Most selections in the three-year study of 22 breeding lines produced yields two and three times higher than the standard USDA lines. Yields of first time regenerated plants compared to the second time regeneration appear to be consistent. It appears feasible to harvest the selected lines at least three times, at two-to-three-year intervals. Five of these lines were placed in the Guayule Uniform Regional Variety Trial conducted across California, Arizona, New Mexico, and, Texas. One proved to be the top yielding line of the 17 included in the study, over all locations.

Indications from the first data set of the parent-progeny study are that a much higher than expected rate of recombination is taking place. Extensive variation for all characters was found among progeny plants when

compared to the parents. Regressions of parent-progeny were not significantly different from zero, which implies very low heritabilities for the major components of yield. Polymorphisms were found for two isozyme systems, indicating existence of genetic variability among and within the apomictic lines. We conclude that family selection, rather than single plant selection, may generate higher yielding and more genetically uniform lines at an escalated rate. Testing of this hypothesis is underway.

Additional single plant selections have been made from other replicated yield trials. These selections are based upon the same criteria as in the 22-line study. Progeny from both single plants and bulk lines will be planted next spring. The top selections will be included in the next Guayule Uniform Regional Variety Trial to be planted in 1994.

Sexual diploid plants for recurrent selection will be harvested and analyzed this spring. Seed from superior plants will be collected, planted, and then recurrently selected. The sexual-by-apomictic hybrids, and new lines planted at closer spacings will also be harvested Spring 1993.

INTERPRETATION: Our single plant selections have proven successful compared to check varieties. These selections have increases in rubber yield up to three times higher than the standard USDA lines. The selections also performed well in the Guayule Uniform Regional Variety Trial. One selection from our program was the top yielding line harvested after two years growth over all locations in the study. This indicates that their performance is not restricted to one location. It has been taken for granted that the amount of sexual recombination in a facultative apomictic plant is about fifteen percent or less. The parent-progeny study presents evidence that a much higher rate is occurring. The study also indicates that another breeding strategy may be more appropriate for the amount of outcrossing taking place in guayule.

FUTURE PLANS: We will continue our effort developing the single plant selections, and the recurrent selection of sexual diploids. We hope to expand our isozyme identification for use as genetic markers to obtain more precise estimates to characterize lines for outcrossing and heritabilities. We also plan to incorporate Polymerase Chain Reaction (PCR) technology to our program. This technique amplifies small quantities of DNA from a plant and shows whether variation is present between plants. The variation detected would be a total result of genetic contribution, since environmental influence is not a factor. New germplasm will be collected and evaluated from Fort Stockton, Texas. Close cooperation will be taking place at this site due to the large amount of germplasm already established there.

COOPERATORS:
Dr. D.T. Ray, The University of Arizona, Plant Science Department, Tucson, AZ
Dr. M.A. Foster, Texas A&M Experiment Station, Ft. Stockton, TX

GERMPLASM IMPROVEMENT OF VERNONIA

A.E. Thompson and D.A. Dierig, Research Geneticists; and
F.S. Nakayama, Research Chemist

PROBLEM: Vernonia galamensis produces seed oil with high quantities of epoxy fatty acids (EFA) that are useful in many industrial applications. These oils can be used in the reformulation of oil-based (alkyd-resin) paints and other coatings to reduce emissions of pollution-causing volatile organic compounds (VOC) or solvents. The EFA are also important ingredients for PVC and other plastics, polymer blends, baked coatings, adhesives, and cosmetics. No other germplasm found to contain naturally occurring epoxy oils has such good potential for commercialization. Until recently, all available Vernonia galamensis germplasm from Africa required short-day photoinduction to induce flowering and subsequent seed production. This prevented successful culture of vernonia within the continental United States. However, one accession, A399 (V029), of the subspecies galamensis var. petitiana was found to be day neutral and to flower any time of the year in Arizona and at other latitudes in the United States. It has some undesirable plant characteristics that limit its direct domestication and utilization. The objective of this research is to develop high-yielding germplasm and cultivars, with adaptation to the United States through hybridization and selection, and to evaluate vernonia's potential for full commercialization as a new industrial oilseed crop.

APPROACH:

1. Evaluate and enhance germplasm of vernonia for high seed oil yield and fatty acid content, day neutral flowering, autofertility, vigorous seed germination, emergence, and seedling growth, and good mature seed retention, using appropriate breeding, genetic, and cytogenetic techniques.
2. Make appropriate genetic crosses, select, test, and develop high-yielding cultivars capable of full commercialization.
3. Work cooperatively with private industry and other public research entities to expedite full commercialization.

FINDINGS: Vernonia galamensis constitutes a species complex of six subspecies, one of which contains four varieties. Crossing barriers between the subspecies and varieties were examined. A common number of chromosomes (n=9) was found in all accessions examined cytologically. No barriers to crossing have yet been found, and meiotic behavior appeared to be normal within and between species and hybrids. Good seed set without pollination, or autofertility, was observed among most of the F1 plants in the various crosses grown in the greenhouse.

A series of crosses was made utilizing A399 (V029, subsp. galamensis var. petitiana), which is autosterile, as the female parent, with A382 [V001, subsp. galamensis var. ethiopica (52 crosses)]; A388 and A389 [V003 & V004, subsp. galamensis var. galamensis (12 crosses)]; A437 [V013, an accession from Tanzania that has not been classified as to subspecies and variety (4 crosses)]; and A390 [V018, subsp. mutomensis (1 cross)]. In total, 359 F1 plants from these 69 crosses were grown in the greenhouse to produce F2 seed for planting and subsequent selection in the field during the summer of 1992. A large majority of the F1 plants (289) was from the 52 A399 x A382 crosses.

A total of 139 F2 populations were selected for field evaluation on the basis of evidence of autofertility, seed production, and size of seed heads from the 359 F1s. On March 23, 1992, a total of 100 seeds from each F2 population and the respective parental lines were germinated in seed flats in the greenhouse to determine rate of germination and apparent seed dormancy. The number of seedlings emerging ranged from 0 (5 populations) to 65. Seedling plants were transferred to flats for subsequent transplanting into the field on May 1, 1992. It was reasoned that selection of early germinating seedlings would tend to eliminate those with undesirable residual seed dormancy. On May 20, 2,086 plants (1,503 from the A399 x A382 crosses) had survived in the field, and classification for a visible flowering response was initiated. As of June 1, 1992, 35% of the F2 plants in the A399 x A382 crosses were classified as flowering. At this time, all of the A399, but none of the A382, parental plants were flowering. Percentages of F2 plants flowering for the other hybrids were: A399 x A388--30%; A399 x A389-- 9%; A399 x A437--16%; and A399 x A360--32%. On July 16, 1992, the last classification was made, at which time 70% of the plants were flowering. On August 12, 1992 a total of 65 single plant selections were made, which represents

only about 3% of the total F2 populations. At this time an estimated 35% of the plants were dying and appeared to be infected with a soilborne pathogen. Care was taken to select only those plants that appeared to be healthy. *The numbers and percentages selected from each type of cross are: A399 x A382--44 (2.9%); A399 x A388--5 (4.6%); A399 x A389--(8.0%); A399 x A437--9 (2.5%); and A399 x A360--1 (2.3%). Of the 65 plants selected, about 72% had flowered by June 20.

A significant finding was the expression of determinate flowering and concentrated seed set which was observed in fewer than 1% of the population. Of the 65 selections made, 15 were classified as determinate, 10 semi-determinate, and 40 indeterminate. Seeds from each selection were harvested individually by hand, and then cleaned, weighed, and 100-seed weights determined.

A network of cooperating scientists from USDA-ARS, State Agricultural Experiment Stations, and industry in Oregon, Colorado, Iowa, Virginia, Georgia, Louisiana, Oklahoma, Texas, and California was developed to evaluate a selected portion of the F2 populations. The cooperators had varying successes with the plantings. A varying number of single plant selections were made at the various locations. Of special interest is the good flowering response observed under the long-day growing conditions in the most northerly locations in Oregon and Iowa.

INTERPRETATION: The genetic segregation within and the performance of the various F2 populations in Arizona and the various locations throughout the country were very encouraging. It is now obvious that the day-neutral flowering response of var. petitiana (A399) can be successfully transferred by conventional hybridization with other subspecies and varieties. It has been fully demonstrated that selection within the segregating F2 populations can isolate new genetic recombinations with such desirable characters as flowering under long daylengths, determinate flowering and concentrated seed set, lack of seed dormancy, and vigorous seedling growth, autofertility, and possibly good mature seed retention, and tolerance to soilborne pathogens. The positive results provide a sound basis for proceeding with full-scale development of vernonia as a new industrial oilseed crop.

FUTURE PLANS: Seeds from the 65 F2 selections made in Arizona and additional selections made at different locations by cooperating scientists will be analyzed for seed oil and vernolic acid contents at the NCAUR, Peoria, IL, and grown in research plots at the University of Arizona Maricopa Agricultural Center for further evaluation and selection. Seeds from selected F2s will also be distributed to cooperating scientists for their further evaluation and selection under their own conditions. The possibility of establishing a winter nursery in 1993 for advancing generations in the new breeding material in some area such as Puerto Rico will be explored. Research on developing appropriate cultural and water management systems is planned for initiation in 1994.

COOPERATORS:

R. Kleiman and K.D. Carlson, USDA-ARS-NCAUR, Peoria, IL
W.W. Roath, USDA-ARS-NCRPIS, Ames, IA
E.V. Wann, USDA-ARS-SCARL, Lane, OK
M.A. Foster, Texas A&M Experiment Station, Fort Stockton, TX
R.J. Roseberg and S.J. Knapp Oregon State University, Medford and Corvallis, OR
D.L. Johnson, Colorado State University, Fort Collins, CO
H.L. Bhardwaj, A.I. Mohamed, M.E. Kraemer, and M. Rangappa, Virginia State University, Petersburg, VA
C.W. Kennedy, Louisiana State University, Baton Rouge, LA
S.C. Phatak, Georgia Coastal Plains Experiment Station, Tifton, GA
J.M. Nelson, University of Arizona MAC, Maricopa, AZ
A.N. Mamood, University of Arizona, Tucson, AZ
A. Hill, Agrigenetics Co., Woodland, CA
J.H. Brown and J.D. Arquette, International Flora Technologies, Apache Junction, AZ

GERMPLASM IMPROVEMENT AND COMMERCIALIZATION OF LESQUERELLA

A.E. Thompson and D.A. Dierig, Research Geneticists;
F.S. Nakayama, Research Chemist; and D.J. Hunsaker, Agricultural Engineer

PROBLEM: The development of lesquerella as a new industrial oilseed crop for the production of hydroxy fatty acid would significantly contribute to the improvement of American agriculture and the general economy of the country. Initial genetic and agronomic research conducted at this location has given encouragement to a full-scale commercialization effort. Cooperative utilization and applications research by both industry and the USDA-ARS National Agricultural Utilization Research Center (NCAUR), Peoria, Illinois, have further stimulated the developmental effort. The objectives of this research are to evaluate and develop improved, high-yielding germplasm and to assess the potential for full commercialization.

APPROACH:

1. Collect, evaluate, and enhance lesquerella germplasm for increased seed, seed oil, and hydroxy fatty acid yields; increase seed size and plant height; promote earlier flowering and seed set; and encourage other improved plant-growth characteristics by using appropriate breeding, genetic, and cytogenetic techniques.
2. Make appropriate genetic crosses; select, test, and develop high-yielding cultivars or hybrids capable of full commercialization.
3. Work cooperatively with private industry and other public research entities to increase basic and applied research, and to increase lesquerella seed volume, quantities. etc. for pilot-plant oil extraction and evaluation, oil and meal utilization, and new product development for full commercialization.

FINDINGS: An experiment was conducted to evaluate an array of breeding lines and to make further selections for high oil and lesquerolic acid content on an individual plant basis. Oil and fatty acid analyses of about 500 seed samples from individual plant selections were completed at the NCAUR. Oil percentages, uncorrected for moisture content, ranged from 13% to 31%, and lesquerolic acid ranged from 42% to 60%. A total of 56 plants, about 10% of the total population, were selected for having the highest combination of both oil and lesquerolic acid contents, and high seed yield. The mean oil content of the 56 selected plants was 26.7%, ranging from 23.5% to 31.4%. Mean lesquerolic acid content was 53.1%, ranging from 48.1% to 60.4%. Progenies of highest yielding selections were planted in the field on Oct. 9, 1992, in a replicated experiment to determine those with the highest yield and the efficacy of selection for high oil yields on a single plant basis.

Progenies of a number of single plants selected for early flowering were evaluated. Several progenies produced a high percentage of plants that started flowering from 2 to 3 weeks earlier than usual, some as early as 15 January. Seed set on most of these early flowering plants was not good, most likely because inadequate activity of bees and other pollinators at this time of year. Many of the plants in the total population were screened for autofertility by bagging the still-unopened flowers before anthesis. A number of plants, some of which were early flowering, were identified as possibly autofertile and not requiring insect pollination for effective seed set. Progenies of these selections are currently being evaluated.

A 20-acre pilot seed production field was planted in October 1991 at the University of Arizona Maricopa Agricultural Center (MAC). Funding from industry cooperators and the USDA Office of Agricultural Materials helped defray expenses. On half the acreage, a large-scale replicated planting methods experiment was imposed to compare planting on the level and on 20", 30" and 40" raised beds. Unfortunately, on May 29, about two weeks before harvest was to take place, a heavy rainstorm with hail delivered about 1" of rain in about 45 minutes, causing severe loss of seed by shattering. Rainfall at this time of year at this location is an extremely rare event, since hardly a trace of rainfall has ever been recorded here. Previously, we had tested for shatter resistance by making applications of up to 1" of water delivered for a period of one hour's duration by sprinklers on fully mature plantings that were ready to combine harvest. Under these conditions, we had not observed any detectable loss of seed by shattering. Instead of the expected 1,500 to 1,600 lbs/acre seed yield, we recovered fewer than 200 lbs/acre. This significantly reduced the expected supply of seed that was to be used for utilization research and additional planting stock for the 1992-93 plantings. About 24 shatter-resistant plants were selected and seeds harvested for further evaluation and selection.

A cooperative effort was initiated with the USDA-ARS Carl Hayden Bee Research Laboratory, Tucson, Arizona. They provided and tended honey bee hives for pollination of the 20-acre pilot production field at MAC. Higher seed set was obtained in the areas of the field that were closest to the hive locations. Evaluation of the quality of honey obtained is in progress.

A detailed proposal was prepared for approval for funding a major germplasm collection effort throughout the country over a three-to-four-year period, starting in the spring of 1993. In addition to the collection of Lesquerella species, the proposal also encompasses the collection of species of Physaria, a closely related genus. The proposal was submitted to the W-6 Technical Committee for approval which was granted. Full funding of the proposal is anticipated in FY-93.

The Lesquerella Commercialization Taskforce met twice at MAC and Phoenix on June 11 and July 9 to evaluate progress and to develop a strategic plan for the timely development of the program. The advent of the Alternative Agriculture Research and Commercialization (AARC) Center funding has provided a viable opportunity for stimulation of the lesquerella commercialization effort. An AARC preproposal was prepared and submitted in October 1992, under the leadership of Agrigenetics Company, which also involves SVO Enterprises/Lubrizol, International Flora Technologies (formerly Jojoba Growers & Processors), the USDA-ARS New Crops Research Unit at NCAUR, Peoria, Illinois, and the New Industrial Crops Breeding and Genetics group at the USWCL, Phoenix, Arizona. The anticipated funding for this program will provide new support for cooperative agronomic and genetic research with the University of Arizona at MAC and with state experiment station cooperators at other locations.

INTERPRETATION: Even though the untimely heavy rainfall severely disrupted project plans for seed harvest, significant progress was made. The major future role of USWCL research effort is to provide the lead in new germplasm collection and evaluation, genetic enhancement of germplasm, and the development of improved varieties or hybrids. The second role is to provide leadership and coordination in the development of a viable crop-management system encompassing plant establishment, weed and pest control, water management, and mechanization. Continued research on water use efficiency and timing of water application is clearly needed. The preliminary results of the selection program for high oil and fatty acid yields are promising, and are expected to yield positive results with an immediate target for developing new varieties with the capability of producing 2,000 lbs/acre of seed with an oil content of 30%. However, due to the current low level of inhouse funding which is insufficient to supply the technical assistance needed for timely oil and fatty acid analysis at this location the germplasm evaluation and enhancement and breeding and selection programs are seriously curtailed.

FUTURE PLANS: Research plantings consisting of replicated yield and selection plots and a 20-acre pilot planting for seed production were made in October at MAC will be harvested in May or June 1993. Data will be taken on plant population, plant height, biomass and seed yield, harvest index, 100-seed weight, oil, and lesquerolic acid contents and yields. Special emphasis will be given to the selection for autofertility in both the greenhouse and the field. A recurrent selection block for a new cycle of selection will be planted in 1993, based upon the yield performance of the 1992-93 experiment, utilizing remnant seed from the 1992 single plant selections.

COOPERATORS:

J.M. Nelson, R.L. Roth, A.N. Mamood, J.C. Wade, and P.N. Wilson, University Arizona, Tucson, AZ
J.H. Brown, J.D. Arquette, and K. Dwyer, International Flora Technologies, Apache Junction, AZ
K.A. Walker, B. Phipps, A. Hill, Agrigenetics Company, Eastlake, OH, Goodyear, AZ, Woodland, CA
E.H. Erickson, G.M. Loper, and A.N. Mamood, USDA-ARS, Bee Research Laboratory, Tucson, AZ
M.A. Foster and J. Moore, Texas A&M, Fort Stockton and Pecos, TX
R.J. Roseberg and S.J. Knapp, Oregon State University, Medford and Corvallis, OR
H.L. Bhardwaj, Virginia State Univ. Petersburg, VA
R. Kleiman and K.D. Carlson, USDA-ARS-NCAUR, Peoria, IL
J.C. Roetheli, L.D. Clements, and D.A. Kugler, USDA-CSRS-SPPS Office of Agricultural Materials, Washington, DC
L.K. Glaser, USDA-ERS, Washington, DC

CULTURAL MANAGEMENT OF LESQUERELLA: WATER & STRESS MANAGEMENT

D.J. Hunsaker, Agricultural Engineer; F.S. Nakayama, Research Chemist;
D.A. Dierig, Research Geneticist; A.E. Thompson, Research Geneticist; and W.L. Alexander, Agronomist

PROBLEM: Prior research has indicated the seasonal water requirement of lesquerella is on the order of 550 to 660 mm. However, little is known about the response of the crop to water application during various stages of growth, particularly over the flowering and fruit maturation stages. Such information is necessary before definitive guidelines on irrigation scheduling can be made. The objective of this research is to determine the water use and water stress behavior of lesquerella under various irrigation regimes.

APPROACH: The 1991-92 lesquerella crop was planted in 1.0-m raised beds on 10 October 1991 at the Maricopa Agricultural Center. Water for plant establishment was accomplished by three flood irrigations following planting which totaled 270 mm. The 0.4-ha site was divided into 20 plots, each 6.1 m by 30.5 m, and five irrigation treatments were randomly assigned to the plots. There were four replications. Two neutron access tubes were placed in each plot to a depth of 200 cm and the soil water content was monitored throughout the growing season. Soil water depletion to a depth of 160 cm was used to estimate evapotranspiration over the growing season.

The five irrigation treatments were begun in late February of 1992 and consisted of the following:

Treatment 1 - irrigated every seven days
Treatment 2 - irrigated every 10-12 days
Treatment 3 - irrigated every 10-12 days, except during early flowering (mid-March)
Treatment 4 - irrigated every 10-12 days, except during full bloom (early April)
Treatment 5 - irrigated every 10-12 days, except during fruit maturation (late April)

The depth of water application per irrigation after establishment was 60-75 mm. Irrigation was terminated on May 7, April 23, and April 8, 1992 for Treatment 1, Treatments 2-4, and Treatment 5, respectively. Ammonium phosphate (16:20) was applied at a rate of 112 kg/ha to all plots prior to flowering (late February). Two, 1.0-m^2 subplots were hand-harvested in all replicates on June 16, 1992.

FINDINGS: Total irrigation water applied and estimated seasonal evapotranspiration (ET) are presented for the irrigation treatments in Table 1. Over 160 mm of precipitation occurred during the 1991-1992 lesquerella growing season, which was unusually high for the area. A large portion of the precipitation occurred in early February (40 mm), late March (50 mm) and late May (20 mm) 1992.

Seasonal evapotranspiration ranged from 567 to 666 mm. The highest ET was obtained in Treatment 1 (weekly irrigation) and was between 60 and 100 mm higher than for other treatments. As shown in Fig. 1, much of the seasonal difference between Treatment 1 and other treatments occurred during early March and late in the season after irrigation had been terminated for Treatments 2-5. Semimonthly ET totals (Fig. 1) indicated Treatment 3 was using water at a lower rate than all other treatments during the early flowering period (late March) when irrigation was withheld from that treatment. However, water use for Treatments 4 and 5 which had irrigations withheld in early and late April, respectively, did not differ in their water use from Treatment 2 which did not have irrigation withheld during those periods. With the exception of Treatment 1, all treatments used water at about the same rate during April and May.

A hailstorm in late May just prior to harvest caused tremendous seed shattering and, consequently, the loss of the total seed yield data. However, enough seeds were recovered to analyze seed weight, seed oil content, and lesquerolic acid content. These, along with plant dry weights are given for the treatments in Table 2.

Plant dry weight, seed oil content, and lesquerolic acid yield were significantly higher for Treatment 1. On the other hand, Treatment 5 which had the lowest plant dry weight had the highest lesquerolic acid content, while Treatment 4 which had the lowest seed oil content had the highest seed weight.

INTERPRETATION: The range in water use for lesquerella in the 1992 harvest year was similar to that of previous studies in 1988, 1989 and 1991. Seasonal ET for plots irrigated on a 10-12-day interval was about the same whether or not an irrigation was withheld. One of the reasons may have been the higher than normal seasonal rainfall that kept the plots from becoming significantly water stressed during the period when an irrigation was not given. A weekly irrigation interval increased ET over a 10-12-day irrigation interval by about 85 mm. The significant increases in seed oil content and lesquerolic acid yield for weekly irrigated plots suggest that more frequent irrigation may be beneficial, somewhat contrary to findings from earlier studies. However, without seed yield determinations for the 1991-1992 experiment, the results are inconclusive.

FUTURE PLANS: Research on lesquerella water use and response to water stress will continue in a 1992-1993 field study. This experiment will be expanded to include eight irrigation treatments, including four water-stress treatments during various stages of growth. Another focus of the experiment will be to determine whether supplemental irrigations given in the early stage of crop development can increase seed yields.

COOPERATORS: J. Nelson, Agronomist, The University of Arizona, Maricopa Agricultural Center.

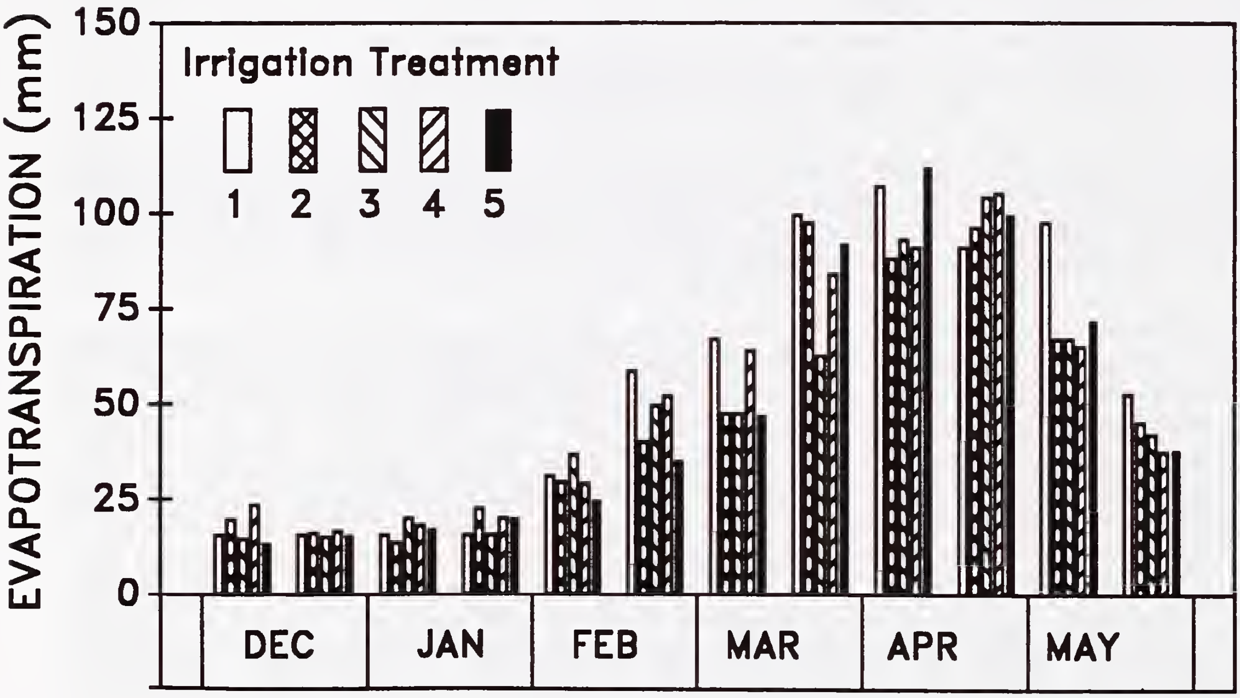

Figure 1. Semimonthly evapotranspiration for irrigation treatments in the 1991-1992 lesquerella experiment.

Table 1. Total water applied and estimated seasonal evapotranspiration for 1991-1992 lesquerella.

Irrigation Treatment	Number of Irrigations	Total Water Applied[1] (mm)	Seasonal Evapotranspiration[2] (mm)
1	7	712	666
2	4	510	582
3	3	453	567
4	3	452	606
5	3	456	586

[1] Includes 270 mm of water from three post-planting irrigations for crop establishment.

[2] Estimate includes soil water depletion (0-160-cm depth) plus 160 mm of rainfall.

Table 2. Yield components for 1991-1992 lesquerella.

Irrigation Treatment	Plant Dry Weight (kg/m^2)	Seed Weight (g/100)	Seed Oil Content (%)	Lesquerolic Acid Content (% of Oil)	Lesquerolic Acid Yield (%)
1	4673[a]	0.053[b]	21.9[a]	53.2[b]	11.7[a]
2	3459[c]	0.059[ab]	18.2[bc]	53.6[b]	9.8[b]
3	4004[b]	0.053[b]	18.6[b]	53.0[b]	9.9[b]
4	3675[bc]	0.063[a]	16.8[c]	53.6[b]	9.0[b]
5	3200[c]	0.061[a]	17.7[bc]	55.4[a]	9.8[b]

[abc] Means followed by different letters in a column are significantly different at the 95% probability level.

LABORATORY SUPPORT STAFF

ELECTRONICS ENGINEERING LABORATORY

D. E. Pettit, Electronics Engineer

The Electronics Engineering Laboratory is staffed by an Electronics Engineer whose duties include design, development, evaluation, and calibration of electronic prototypes in support of U. S. Water Conservation Laboratory research projects. Other responsibilities include repairing and modifying electronic equipment and advising staff scientists and engineers in the selection, purchase, and upgrade of electronic equipment.

Support provided to research projects in 1992 included conversion of a video splitter/amplifier to accept a 12-volt power supply for use in an airborne thermal imaging system (see Clarke, "Airborne Thermal Imagery as a Farm Management Tool," p. 75 in this report).

Digital propeller speed sensors were modified for use inside irrigation pipe to record and display long-term averages and peaks of fluid flows (see Replogle and Wahlin, "Irrigation Flow Measurement Studies," p. 5 in this report).

A high amperage wet cell battery charger was modified with special circuitry to allow the batteries to remain at rest when fully charged, without overcharging, and then be cycled for short periods (see Idso and Kimball, "CO_2 Enrichment of Trees," p. 59 in this report).

Upgrading of Electronics Shop capabilities has continued, e.g., litho film can now be processed in the Shop, which significantly expedites the building of electronic circuit boards. Storage areas are being modified, and reference materials are being cataloged for improved accessibility.

COMPUTER FACILITY

T. A. Mills, Computer Programmer Analyst

The computer facility is staffed by one full-time Computer Specialist (Terry Mills) and one Computer Assistant (Harold Mastin). Support is provided to all laboratory computer equipment and applications. The facility is responsible for recommending, purchasing, installing, configuring, upgrading, and maintaining the Laboratory computer systems. Systems include a Hewlett-Packard HP 1000, a DEC MicroVax II, over 50 personal computers (PCs), including a PC-based network server. A standard Ethernet backbone connects five laboratory buildings. Four 10Base-T hubs are connected to the backbone. The network is currently supporting Novell Netware 386 3.11 and Digital's DECNET and PCSA.

The major effort during 1992 focused on further implementation of the NOVELL NetWare 3.11 PC-based Local Area Network (LAN) system. At this point, thirty PC's have been connected through standard and 10Base-T Ethernet interfaces. Seven printers are available on the LAN. An office-wide electronic mail system has been installed, along with anti-virus software and several user front ends such as Windows 3.1 and Word Perfect Office. The NetWare file server is an AST 486/25 TE computer with two 1.4 gigabyte SCSI hard drives. We are in the process of installing a network communication server that will provide multiple lines for dialing in and out of the network. We are also expanding our network to include a SUN Sparc Station and two additional high-speed HP Laserjet IIIsi printers at strategic locations.

The process of screening, organizing, and transferring the thousands of programs and data files from the minicomputers to the PC-based LAN has proven to be a major task, with expected completion in early 1993. When the transfer is completed, the two mini-computers will be phased out.

Plans for 1993 include expanding outside communications capabilities and electronic mail and bringing the Location Administration Office into the LAN. Efforts will also be made to include a Macintosh computer in the system.

LIBRARY AND PUBLICATIONS

L. S. Seay, Publications Clerk

Library and publications functions, performed by one Publications Clerk, include maintenance of records and files for publications authored by the Laboratory Research Staff, including publications co-authored with outside researchers,[1] as well as for holdings of professional journal and other incoming media. Support includes searches for requested publications and materials for the Staff. Library holdings include approximately 1600 volumes in various scientific fields related to agriculture. Holdings of some professional journals extend back to 1959.

The U. S. Water Conservation Laboratory List of Publications, containing over 1700 entries, is maintained on PROCITE, an automated bibliographic program. The automated system provides for sorting and printing selected lists of Laboratory publications. Publication lists and most of the publications are available on request.

Compilation of an Auxiliary Laboratory Publications List was begun in 1992. The Auxiliary List will include selected reports and non-peer-reviewed material to facilitate wider dissemination and use.

An automated system for journal holdings is planned.

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[1] Appendix A lists manuscripts published or formally accepted for publication in 1992.

MACHINE SHOP

C. L. Lewis, Machinist

The machine shop, staffed by one full-time and one part-time machinist, provides facilities to fabricate, assemble, modify, and replace experimental equipment in support of U. S. Water Conservation Laboratory research projects. Following are examples of work orders completed in 1992:

Four steady-state canopy gas exchange systems were fabricated for continuous monitoring of carbon and water vapor exchange rates of the ambient, enriched, wet and dry treatments of the 1993 Free-Air Carbon dioxide Enrichment (FACE) wheat experiment. The chambers are 0.75m by 0.75m-wide and 1.3m tall, of aluminum frame construction and have mounting and leveling brackets for an infrared thermometer and quantum light sensor (see Garcia, Idso, Kimball, "CO_2 Enrichment of Pine Trees," p. 49 in this report).

Twenty stainless steel cylinders were fabricated as grinding chambers for the SPEX Ball Mill to grind soil and plant material samples. The cylinders are 2.500" tall with an inside diameter of 1.500". Cylinders and sealing caps are of 316 stainless steel with threaded aluminum lids (see Rice *et al.*, "Nitrogen Fertilizer and Water Transport Under 100% Irrigation Efficiency," p. 28 in this report).

A working model of a desert survival still was constructed for display at the U. S. Department of Agriculture, Washington, DC, as part of the award ceremony honoring Ray Jackson as Outstanding Scientist of the Year for 1992.

Components were added to the milling machine purchased in 1991 that have increased the machine's efficiency significantly.

APPENDIX A

APPENDIX A

Manuscripts Published or Accepted for Publication in 1992

1. ADAMSEN, F.J. Mineral composition of peanut tissue as influenced by irrigation water quality and irrigation method. Commun. Soil Sci. Plant Anal. (ACCEPTED BY JRL-SEP 1992) 6650-14230-001-00D.

2. ADAMSEN, F.J. 1992. Irrigation method and water quality effects on corn yield in the mid-Atlantic coastal plain. Agron. J. 84:837-843. 6650-14230-001-00D.

3. ADAMSEN, F.J., PORTER, D.M., and AULD, D.L. Effects rapeseed meal soil amendments on microsclerotia of Cylindrocladium crotalariae in naturally-infested soil. Peanut Sci. (ACCEPTED BY JRL-AUG 1992) 6650-14230-001-00D.

4. ALBERTSON, M.L., and BOUWER, H. 1992. Future of irrigation in balanced third world development. Agric. Water Mgmt. 21(1-2):33-44. 5344-13000-003-00D.

5. BALLING JR., R.C., IDSO, S.B., and HUGHES, W.S. Long-term and recent anomalous temperature changes in Australia. Geophys. Res. Letter. (ACCEPTED BY JRL-DEC 1992) 5344-11000-004-00D.

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7. BOUWER, H. 1992. Artificial recharge of groundwater--Interdisciplinary Systems. p. 103-106. IN: M.E. Jones and A. Laenen (eds.) Proc. Symp. on Interdisciplinary Approaches in Hydrology and Hydrogeology, Portland, OR. 19-21 Oct 1992. 5344-13000-003-00D.

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9. BOUWER, H. 1992. Water conservation in arid zones. p. 21-31 Chap. 2 IN: E.B.A. De Strooper, M. F. L. De Boodt. H. J. W. Verplancke (eds.) Water Saving Techniques for Plant Growth. Kluwer Academic Publishers, The Netherlands. 5344-13000-003-00D.

10. CARLSON, K.D., KNAPP, S.A., THOMPSON, A.E., BROWN, J.H., and JOLLIFF, G.D. 1992. Other new oilseed crops. Part III, Chap. 7. IN: 1992 Yearbook of Agriculture. 5344-21410-001-00D.

11. CLEMMENS, A.J. 1992. Discussion of "Rational approach for modifying rotational water delivery schedule." J. Irrig. and Drain. Engr. 118(3):507-508. 5344-13000-001-00D.

12. CLEMMENS, A.J. 1992. Feedback control of a basin irrigation system. J. Irrig. and Drain. Engr. 118(3):480-496. 5433-13000-001-00D.

13. CLEMMENS, A.J., and BOS, M.G. 1992. Critical depth relations for flow measurement design. J. Irrig. and Drain. Engr. 118(3):640-644. 5344-13000-001-00D.

14. CLEMMENS, A.J., and DEDRICK, A.R. Chapter 7: Irrigation techniques and evaluations. Management of Water Use in Agriculture. (ACCEPTED BY JRL-04 AUG 1992) 5344-13000-005-00D.

15. CLEMMENS, A.J., and DEDRICK, A.R. 1992. Identifying factors that influence farm water use. Vol II, p. 2.1- 2.11. IN: Pan American Regional Conf. 9-11 Nov 1992. 5344-13000-005-00D.

16. CLEMMENS, A.J., et al. Unsteady flow modeling of irrigation canals. J. Irrig. and Drain. Engr. (ACCEPTED BY JRL-5 MAY 1992) 5344-13000-005-00D.

17. CLEMMENS, A.J., HOLLY, F.M., and SCHUURMANS, W. Description and evaluation of program: Duflow. J. Irrig. and Drain. Engr. (ACCEPTED BY JRL-28 APR 1992) 5344-13000-005-00D.

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21. CLEMMENS, A.J., and SLOAN, G. 1992. Canal Control Challenge. p. 231-240 IN: Proc. Int. Workshop, CEMAGREF-IIMI, The Application of Mathematical Modeling for the Improvement of Irrigation Canal Operation, 26-30 Oct 1992. Montpellier, France. 5344-13000-005-00D.

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24. DEDRICK, A.R., CLYMA, W., CLEMMENS, A.J., GIBSON, R.D., REPLOGLE, J.A., WARE, R.E., WILSON, P.N., and LEVINE, D.B. 1992. An interagency program to improve irrigated agriculture. p. 595-600 IN: Irrigation & Drainage Saving a Threatened Resource-In Search of Solutions. Proc. Irrig. and Drain. Sessions at Water Forum '92. Baltimore, MD. 2-6 Aug 1992. 5344-13000-005-00D.

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26. DIERIG, D.A., THOMPSON, A.E., and NAKAYAMA, F.S. Lesquerella commercialization efforts in the United States. Industrial Crops and Products. (ACCEPTED BY JRL-10 JUN 1992) 5344-21410-001-10D.

27. DIERIG, D.A., THOMPSON, A.E., and RAY, D.T. 1992. Yield evaluation of new Arizona guayule

selections. p. 83-87. IN: Naqvi, H.H., Estilai, A., and Ting, I.P. (eds.) New Industrial Crops and Products. Office of Arid Land Studies, University of Arizona, Tucson, AZ. 5344-21410-001-00D.

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31. GRAYBILL, D.A., and IDSO, S.B. Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in three-ring chronologies. Global Biogeochemical Cycles. (ACCEPTED BY JRL-OCT 1992) 5344-11000-004-00D.

32. GRIES, C., IDSO, S.B., and KIMBALL, B.A. Nutrient uptake during the course of a year by sour orange trees growing in ambient and elevated atmospheric CO_2 concentrations. J. Plant Nutrition. (ACCEPTED BY JRL-JUL 1992) 5344-11000-004-00D.

33. HILEMAN, D.R., GHOSH, P.P., BHATTACHARYA, N.C., BISWAS, P.K., ALLEN JR., L.H., PERESTA, G., and KIMBALL, B.A. 1992. A comparison of the uniformity of an elevated CO_2 environment in three different types of open-top chambers. Critical Reviews in Plant Sciences. 11(2-3):195-202. Also published; Book Chapter, p. 195-202. IN: G.R. Hendrey (ed.) FACE: Free-Air CO_2 Enrichment for Plant Research in the Field. CRC Press, Boca Raton, FL. 5344-13610-001-00D.

34. HUNSAKER, D.J. 1992. Cotton yield variability under level basin irrigation. Trans. ASAE. 35(4):1205-1211. 5344-13000-005-00D.

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37. IDSO, S.B. 1992. Carbon dioxide and global change: End of nature or rebirth of the biosphere? p. 414-433. IN: J.H. Lehr (ed.) Rational Readings on Environmental Concerns. New York, NY. Van Nostrand Reinhold. 5344-13610-001-00D.

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41. IDSO, S.B. 1992. Net photosynthesis: Corrections required of leaf chamber measurements. Agric. & Forest Meteorology. 58:35-42. 5344-11130-004-00D.

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43. IDSO, S.B., and BALLING JR., R.C. 1992. United States drought trends of the past century. Agric. Forest Meteorol. 60:279-284. 5344-11130-004-00D.

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APPENDIX B

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Patents Granted in 1992

1. REPLOGLE, J.A. 1992. Adjustable Flume. 5 pp. United States Patent Number 5,156,489, dated 20 Oct 1992. 5344-13000-005-04S.